IMAGE ACQUISITION AND REPRESENTATION

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Summary

- Image acquisition in the visible spectrum
  - Cameras; sensors
  - Optics (lenses, prisms, filters)
  - Lighting
  - 3D data acquisition (overview)

- Image representation
  - Grayscale and color
  - Color spaces
  - Image resolution (spatial, intensity)

Start your algorithm development with the vision system !

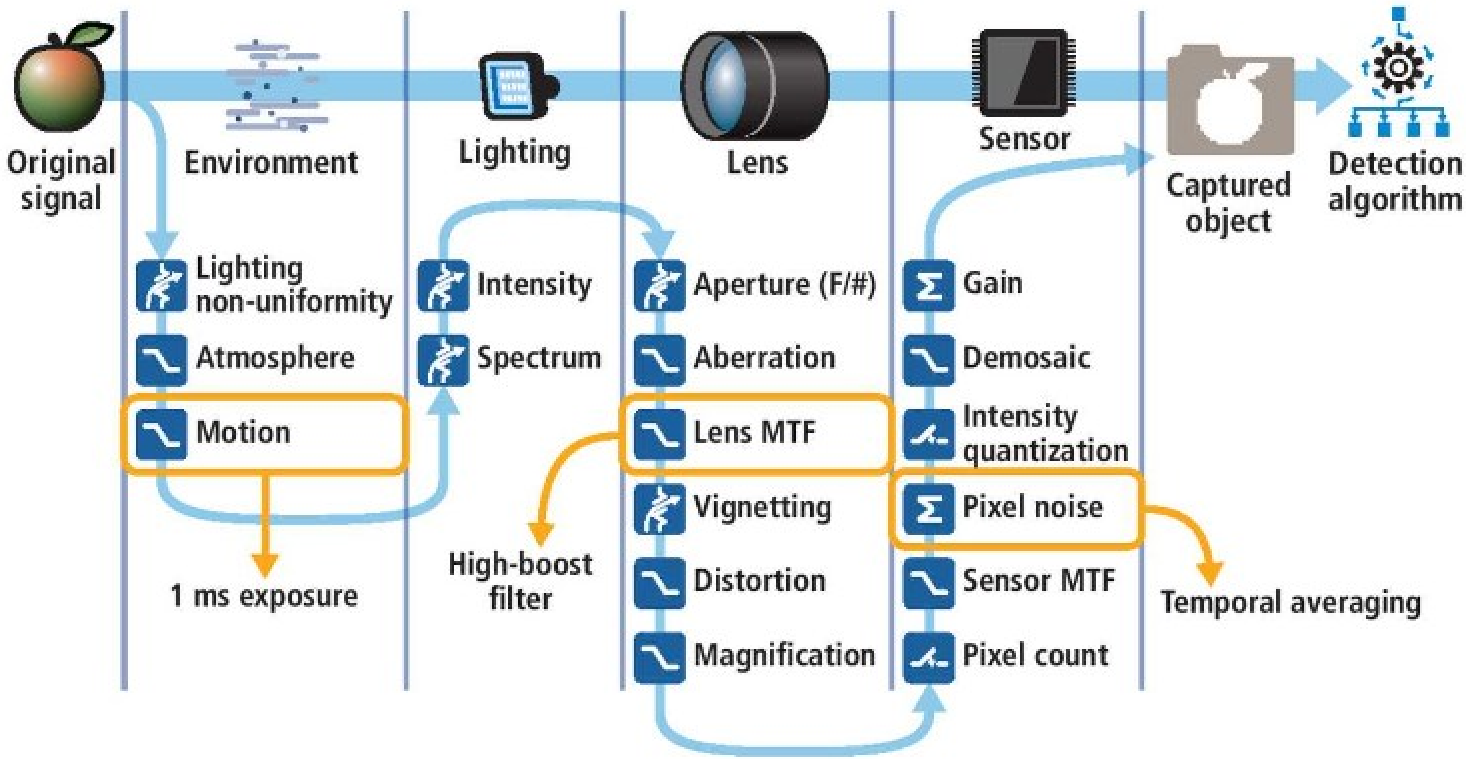
- Starting with the vision system is important for 2 reasons:
  - **Algorithm performance is limited to the image quality produced by the vision system**
    - although increasing algorithm capability is possible, at some point its performance is limited by the quality of the image
  - Vision systems are complex, with many interacting parameters, across multiple components, making it expensive to change parameters late in the development cycle

- Note:
  there are computer vision tasks, like content-based image retrieval (use computer vision to browse, search and retrieve images from large data stores, based on the content of the images rather than metadata tags associated with them) in which you do not have control over the acquisition.

Image acquisition

- It is very difficult to build successful a machine vision applications without the capture of very high quality images
  - **<u>Image quality</u>**:
    correct resolution for the target application
    with best possible feature contrast
    - <u>Resolution</u> –
      determined by characteristics of the sensor and quality of the optics
    - <u>Feature contrast</u> –
      determined by correct lighting technique and quality of optics
- **Imaging is said to contribute more than 80% to the success of any machine vision application**
- **Machine vision algorithms <u>cannot</u> make up much for most of problems resulting from inadequate image acquisition (ex: poor resolution or poor illumination)**

Modeling the signal path



An example of modeling of the signal path; helps developers understand problems and their impact on image quality

"Build-Measure-Learn loop" approach

- At the beginning of development,
  there is often a "chicken or the egg" problem:
  - the image quality produced by the vision system
    will drive the image processing algorithm requirements;
  - the capability of the image processing algorithm algorithm
    will drive the vision system requirements.
- A successful design is one where the capabilities of
  the vision system and the processing algorithm
  are harmonized,
  thereby meeting the business goals.
- During the development,
  both the algorithm and vision system
  must be considered together.
- To do this well, effective iteration is required:
  Build – Measure – Learn loop

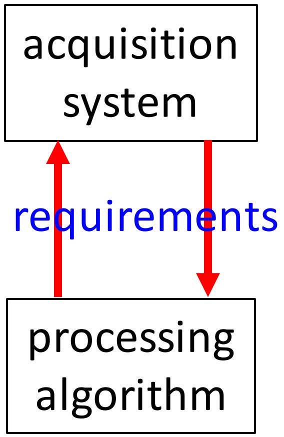
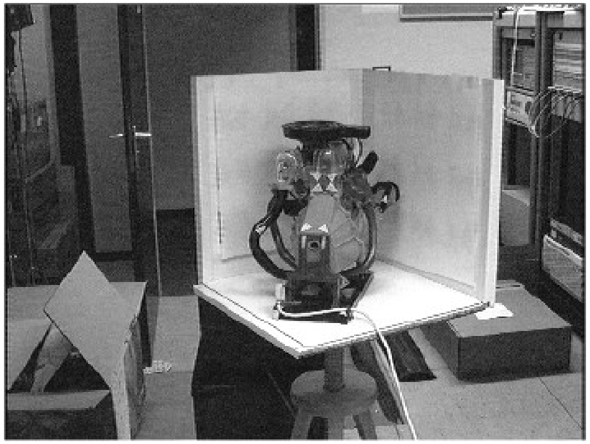


IMAGE ACQUISITION

Image types

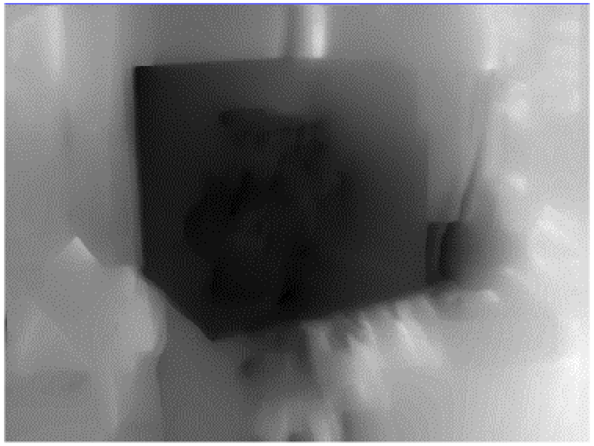
Color image (visible spectrum)

X-ray image



Infrared image

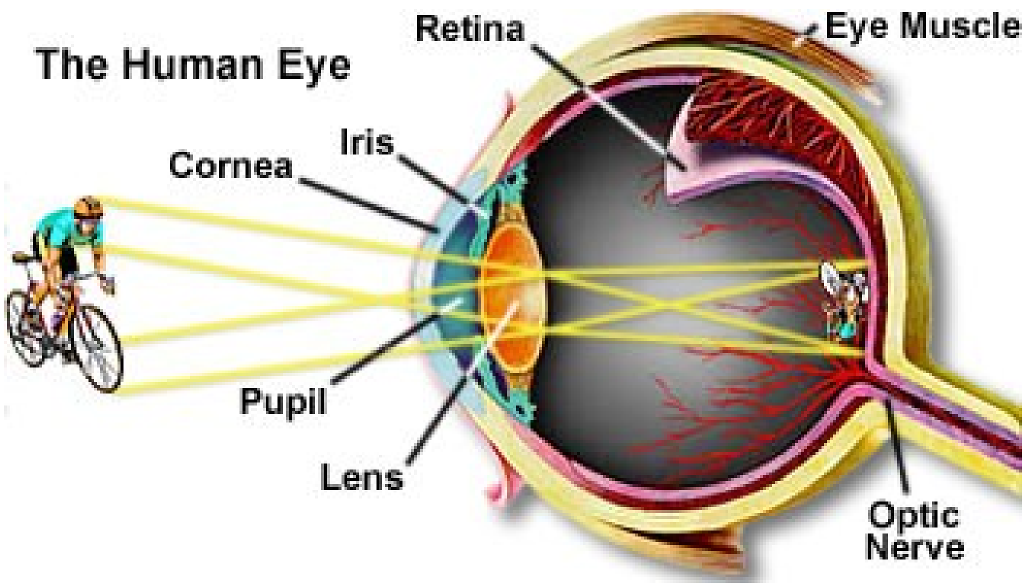
Tomographic X-ray image

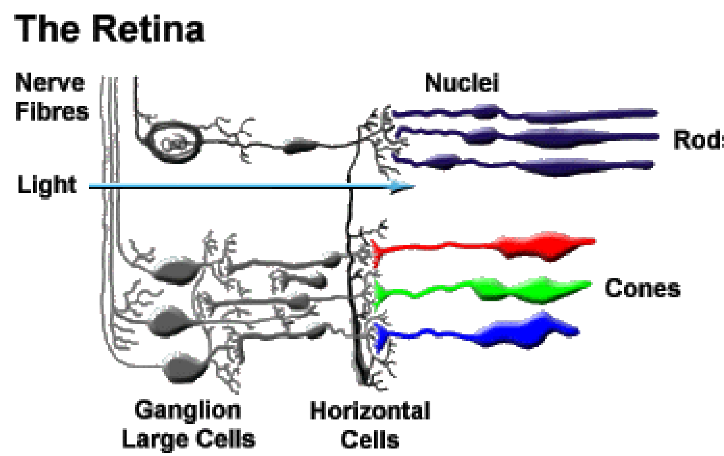


Distance / Range image

IMAGE ACQUISITION
IN THE VISIBLE SPECTRUM

The human eye





retina ↔ film
iris+pupil ↔ aperture
lens ↔ lens

- Focal distance: ~20 mm
- Sensitive to light with wavelength between 400 nm (violet) and 700 nm (red)
- Sensing elements: cells (100 millions)
- Colors: catches 3 separate intensities

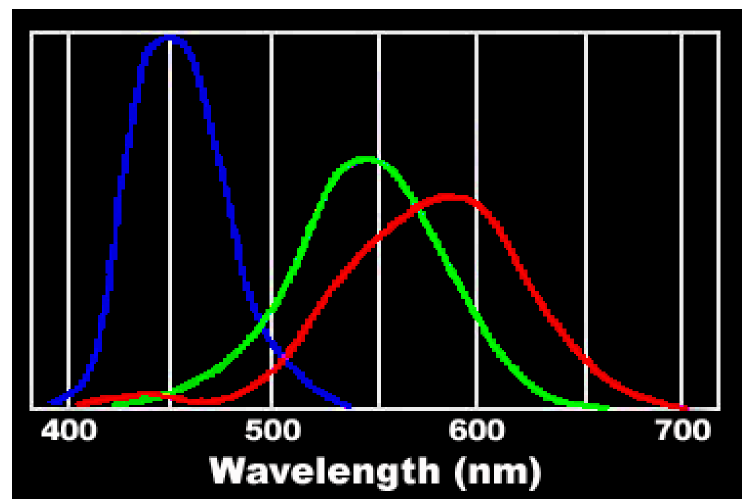
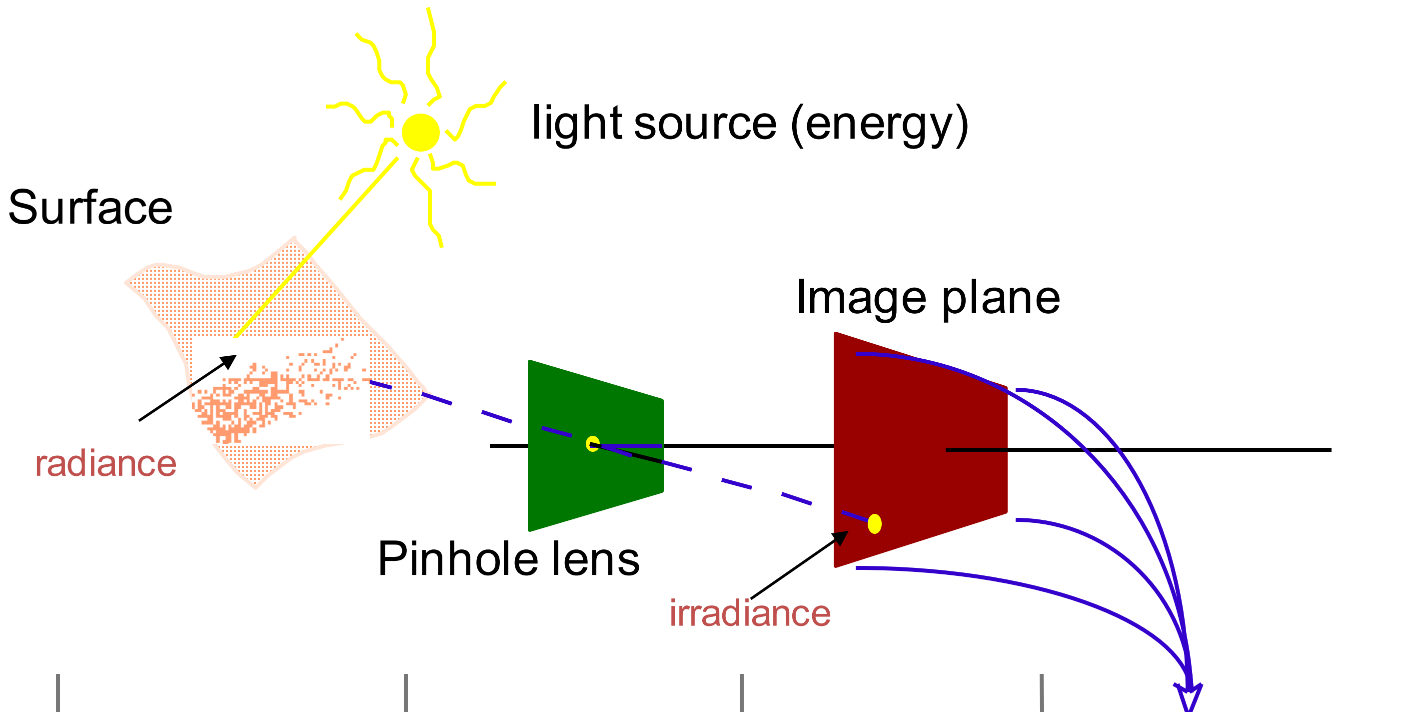


Image formation



World | Optics | Sensor | Signal

Sensor
- film B&W
- film color
- sensor
  CCD
  CMOS
  …

Signal
- silver density
- electrical signal
  (electrical charge)

Image formation

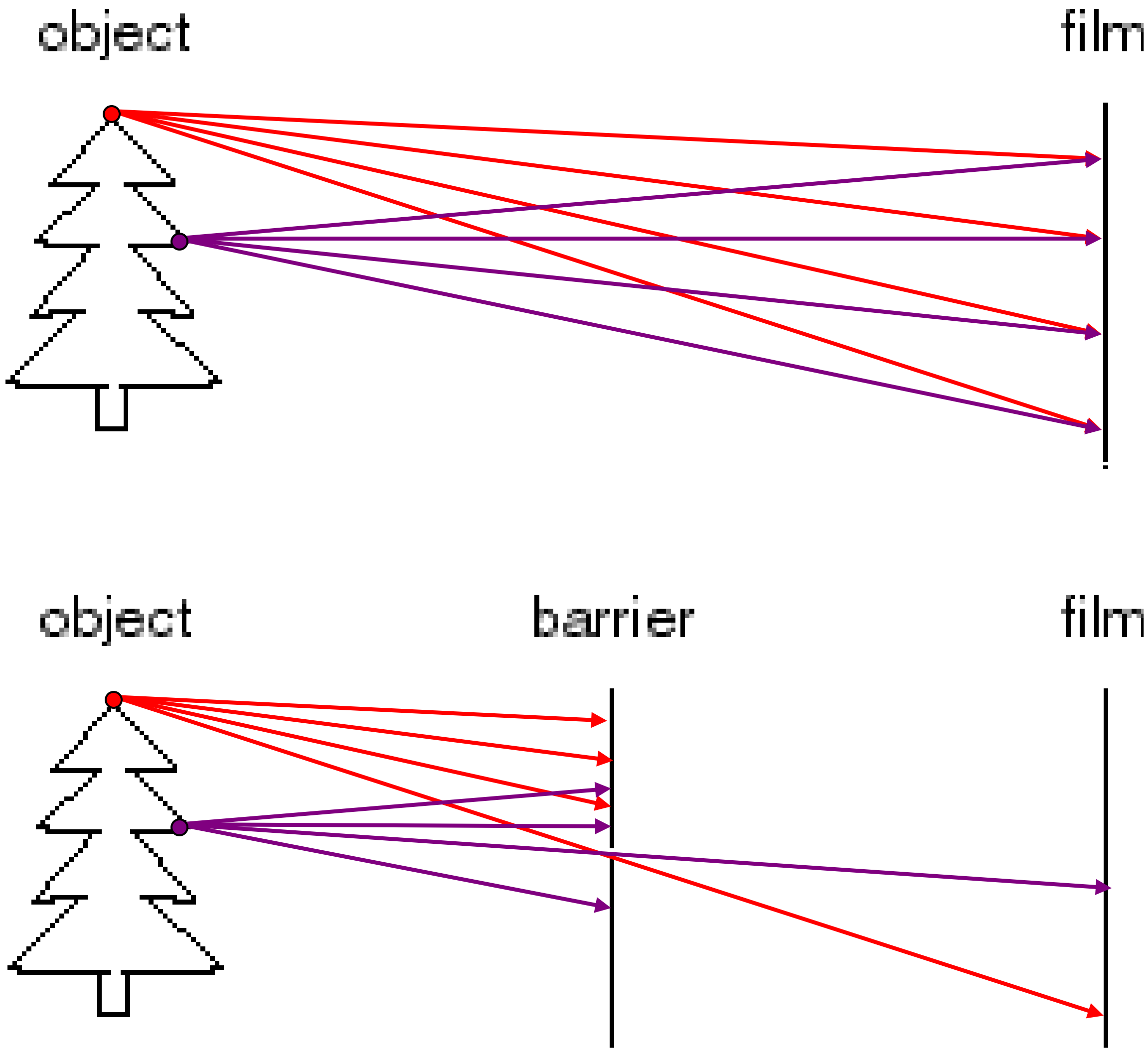
- Geometry
  - deals with the relationship between the 3D coordinates of scene points and the 2D coordinates of the corresponding image points
- Radiometry
  - deals with the relationship between
    the amount of light radiated by a surface and
    the amount of light that falls on the sensor
    - relationship between the brightness of scene points and the brightness of the image points
- Photometry
  - deals with the conversion of the luminous energy into an electric signal
- Digitization
  - deals with the conversion of continuous electronic signals into digital signals, in space and time (sampling and quantization)

Image acquisition system

- Illumination
  - lights
  - filters
- Camera
  - filters
  - lenses
  - sensors
- Computer
  - frame grabbers
  - acquisition modules
- (interface cables)

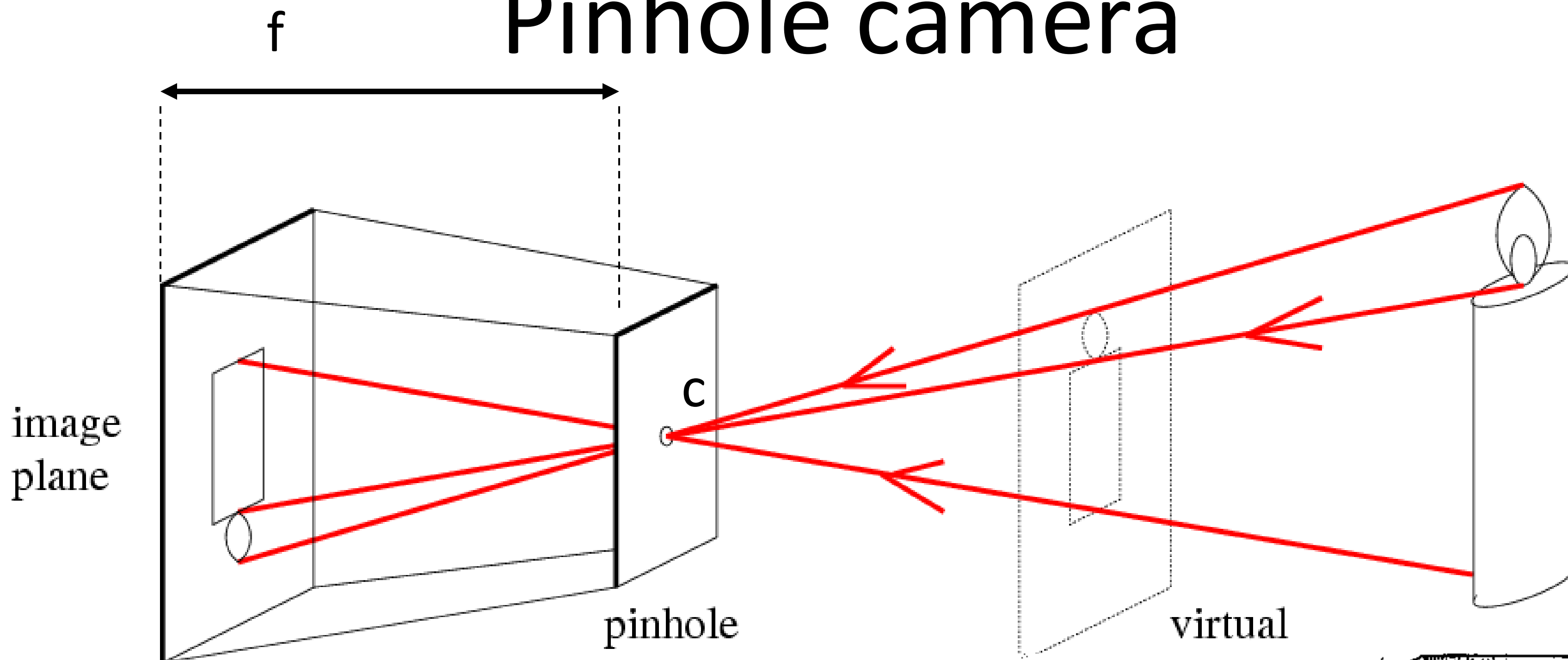
optics

Image formation



Slide source: Seitz

Pinhole camera



f = focal length

c = center of the camera

Source: Forsyth

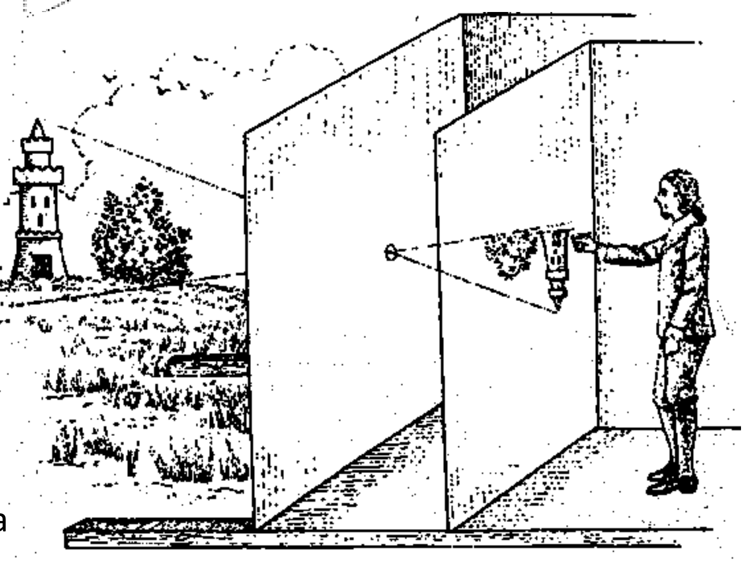
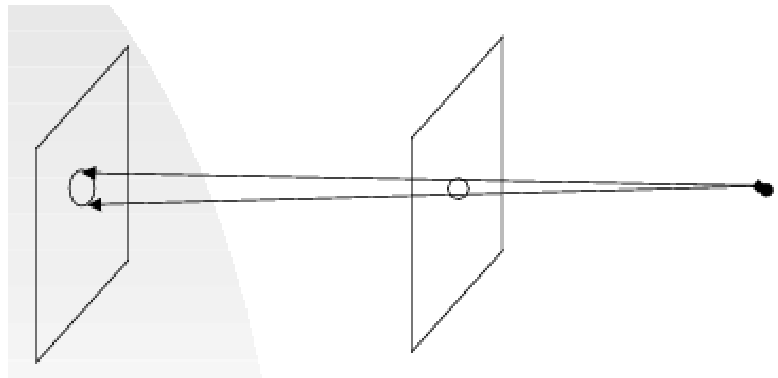


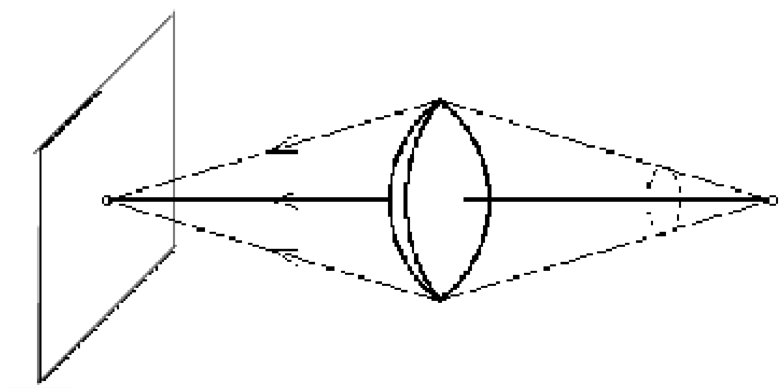
Illustration of Camera Obscura

Pinhole camera

Photo acquired using a pinhole camera
Robert Kosara
(http://www.kosara.net/gallery/pinholeportugal/index.html)

The need for lenses





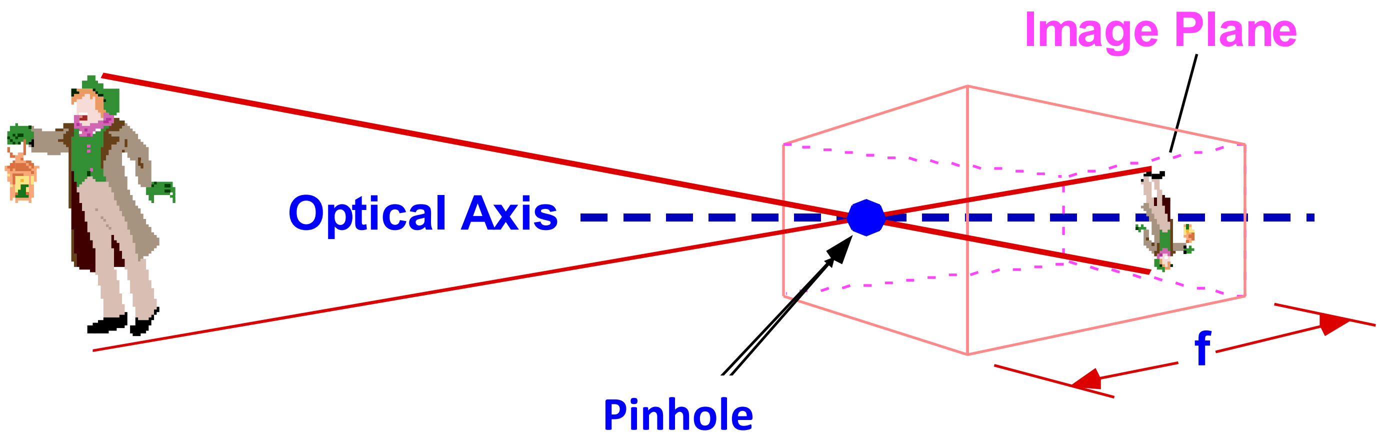
CAMERA

GEOMETRIC MODEL

Geometric model

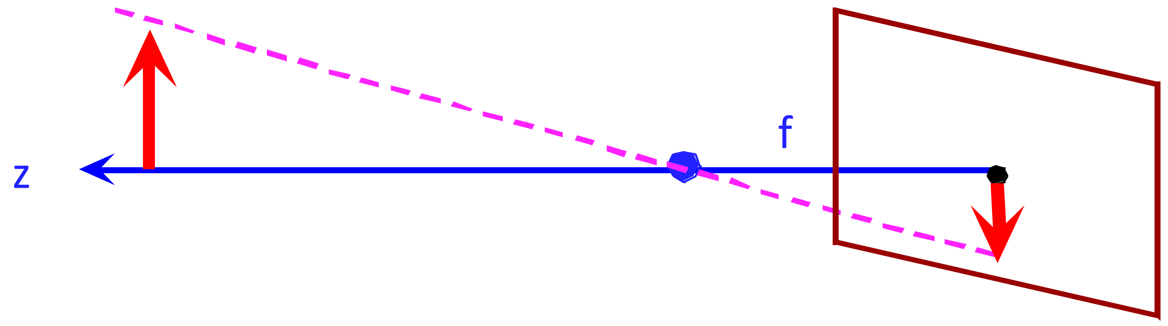
- Model usually used is:
  - Pinhole camera
  - Thin lens
- Geometric model
  - describes, mathematically, the transformation of the 3D coordinates of the scene points into 2D coordinates of the image points, and the inverse transformation
    - note:
      a point in the image corresponds to a line in space
  - several types of projection models
    - perspective
    - weak perspective
    - …

Pinhole model



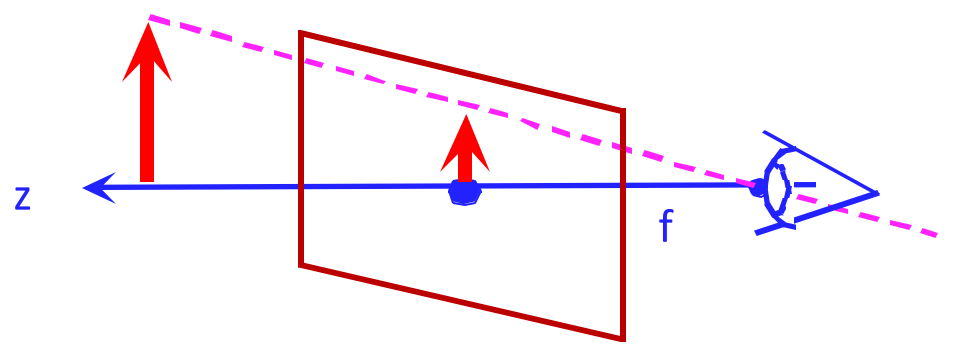
- The world is projected on a 2D plane
  - inverted image
  - small size
  - low contrast
  - distance to the object is lost
- f = focal length of the lens
- Perspective projection

Equivalent geometry

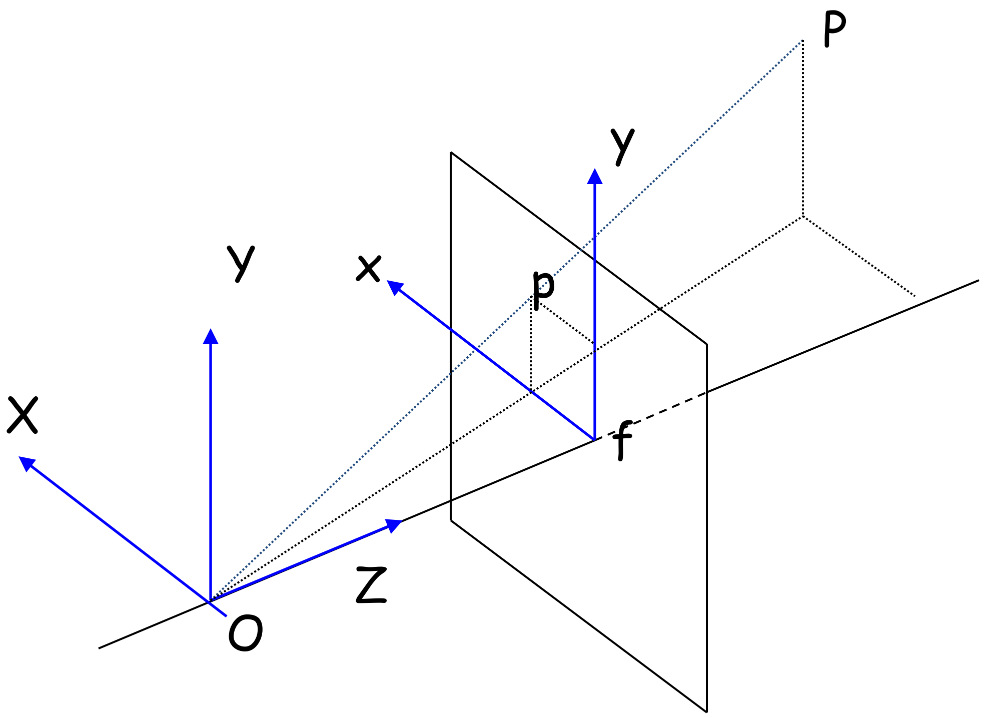


Equivalent image (non-inverted; more convenient)

"Mathematically" equivalent.



Perspective projection

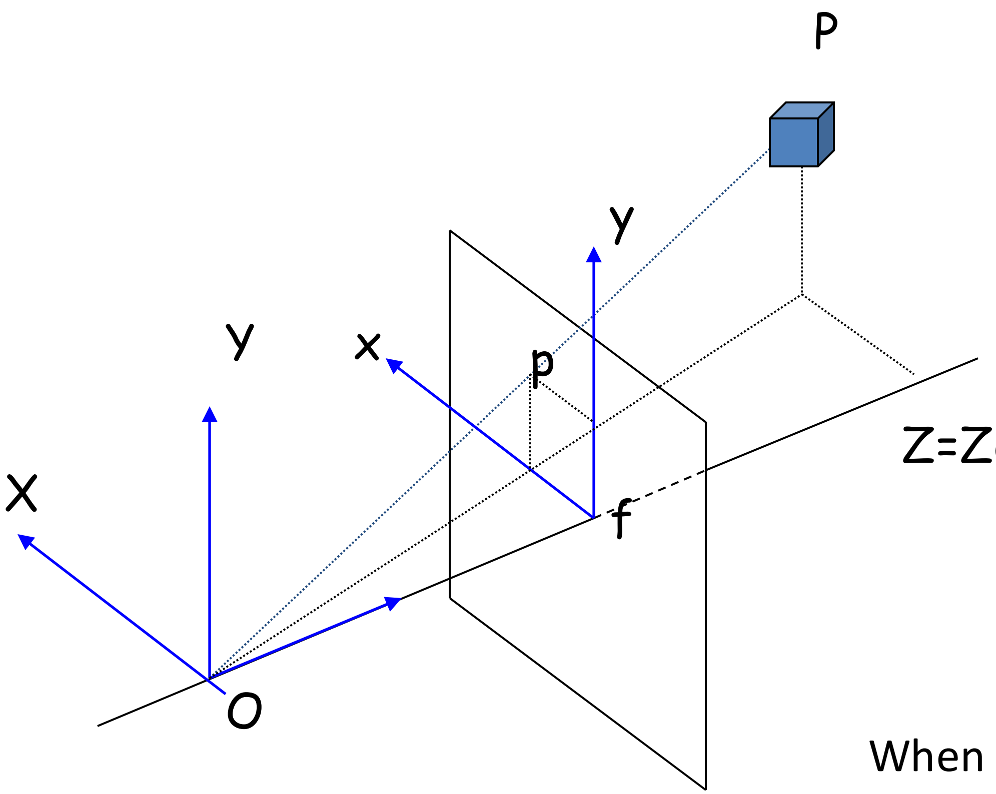


$$x = f\frac{X}{Z}$$

$$y = f\frac{Y}{Z}$$

Note:
this is a non-linear relationship due to the factor *1/z* .

Weak perspective projection



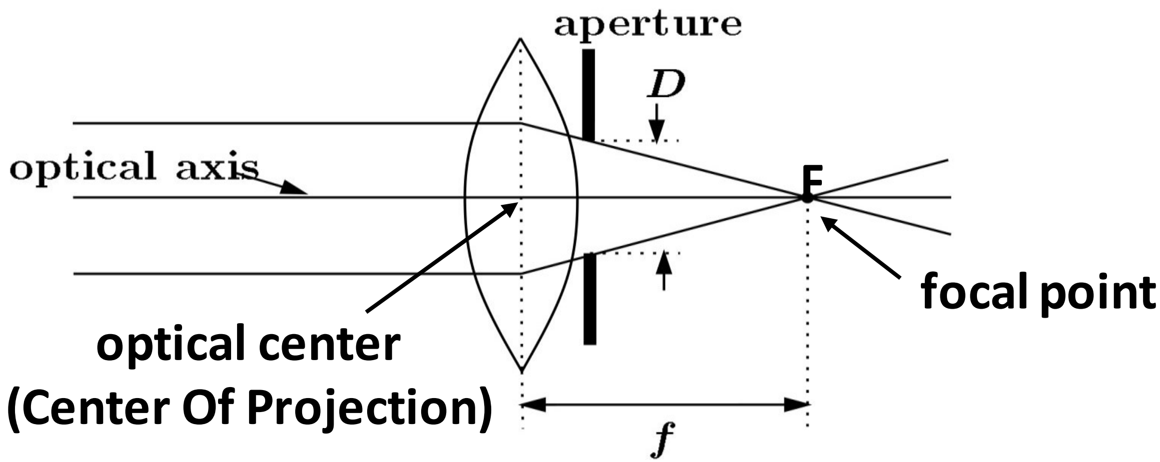
$$x \approx f \frac{X}{Z_o}$$

$$y \approx f \frac{Y}{Z_o}$$

$m = f / z_0 = const.$

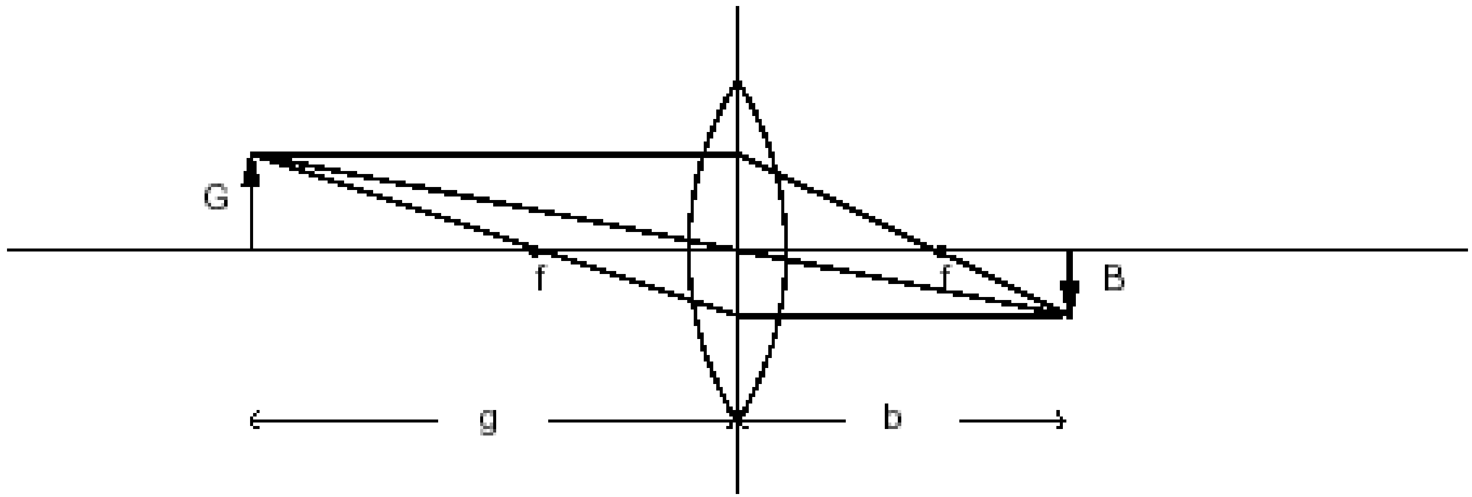
When de distance between any 2 scene points is much smaller than
the average distance to the scene (Zo)
(20 x smaller ? ...).

Lens concepts



- A lens focuses parallel rays onto a single focal point focal point at a distance f beyond the plane of the lens
- Aperture of diameter D restricts the range of rays

Thin lens model



The optics of a thin lens

$$\frac{\mathbf{1}}{g} + \frac{1}{b} = \frac{1}{f}$$

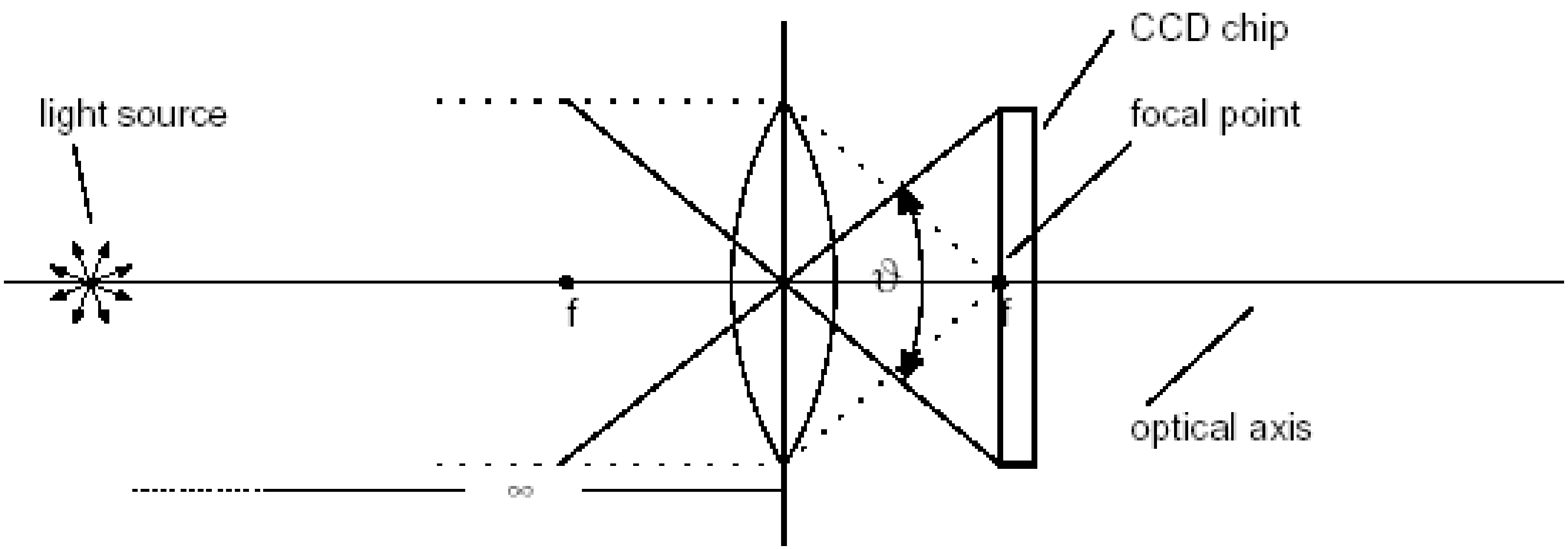
with
b: distance of the image
g: distance of the object
f: focal length

and

$$\frac{B}{G} = \frac{b}{g} = m$$

with
B: height of the image
G: height of the object m: aspect ratio

Angular field of vision



The photographic angle ϑ

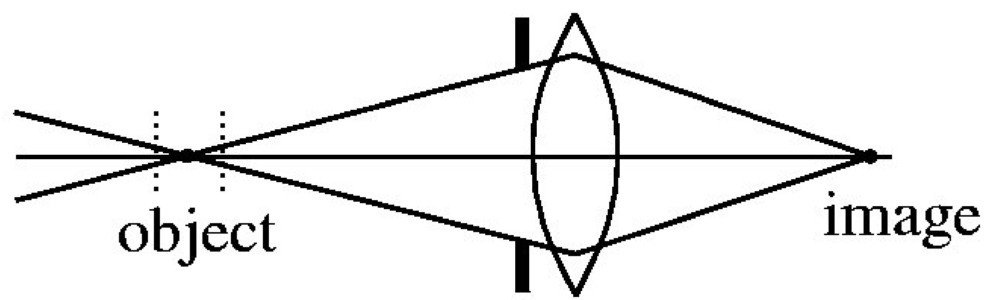
$$\frac{B_{max}}{2f} = \tan\left(\frac{\vartheta}{2}\right)$$
$$\rightarrow \vartheta = 2 \cdot \arctan\left(\frac{B_{max}}{2f}\right)$$

where B_{max} is the length of the diagonal of the chip in the case of area scan cameras

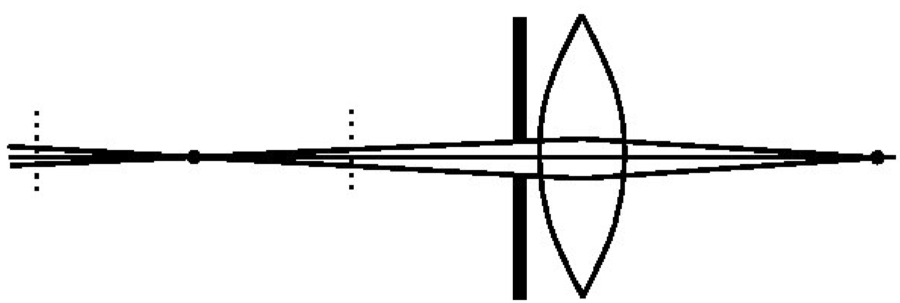
Depth of field

Depth of field

- Changing the aperture size or focal length affects depth of field

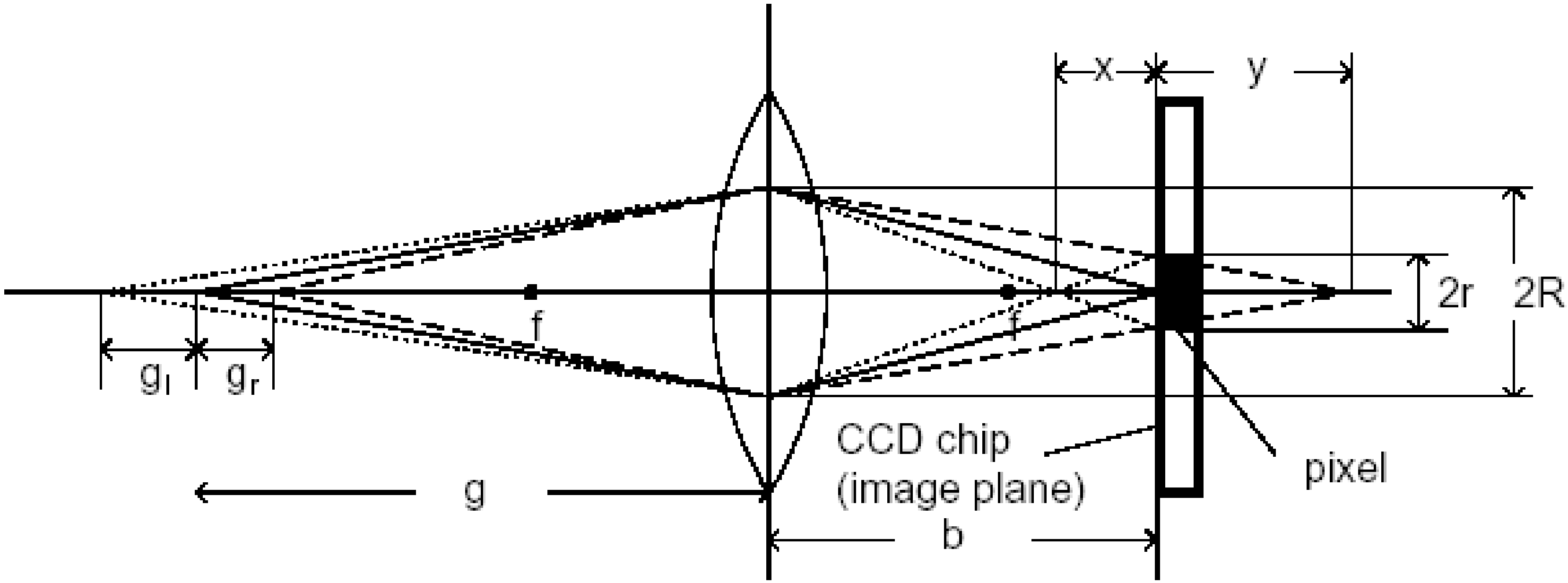


$f / 5.6$



$f / 32$

Depth of field



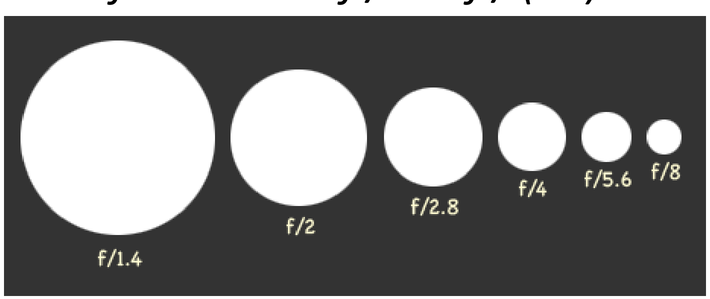
depth of field.calculation

$$g_l = \frac{2rkg(g-f)}{f^2 - 2rk(g-f)} \quad \text{and}$$

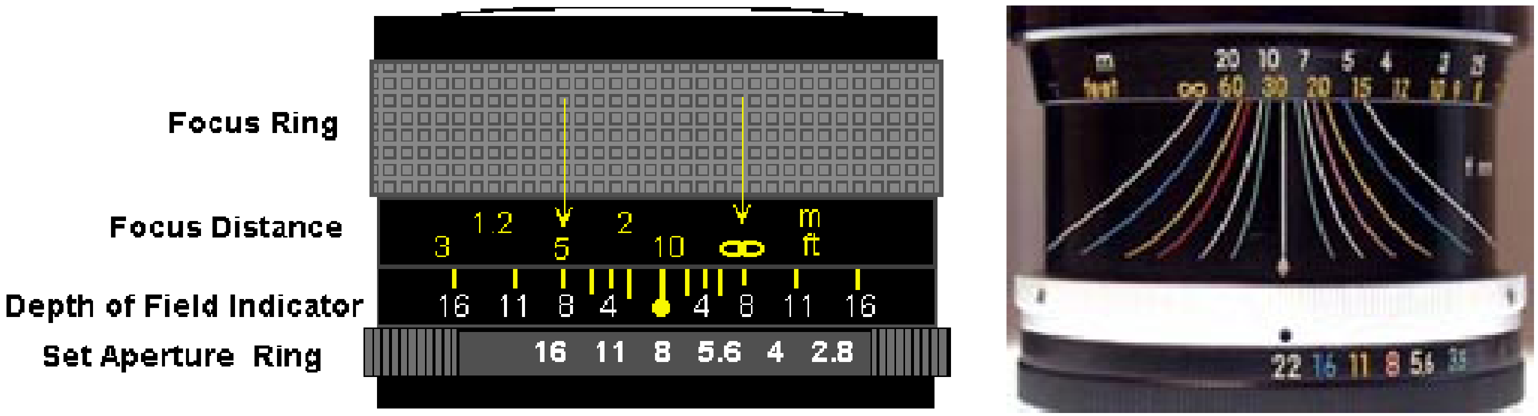
$$g_r = \frac{2rkg(g-f)}{f^2 + 2rk(g-f)}$$

$$\rightarrow g_r + g_l = \frac{4f^2 rkg(g-f)}{f^4 - 4r^2k^2(g-f)^2}$$

f-number = *f / # = f / (2R)*



Zoom lenses



(a) (b)

Regular and zoom lens depth of field indicators.

source: Szeliski's book

- How is magnification varied ?

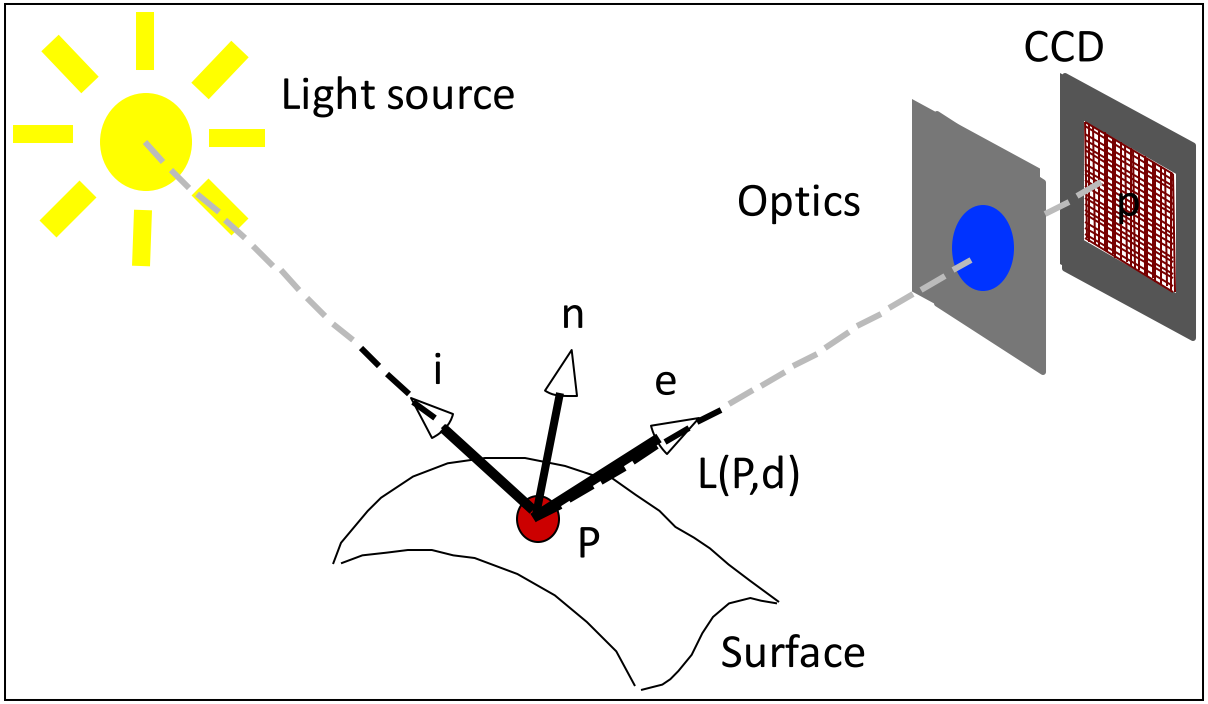
TO DO BY STUDENTS

- Search for information about
  LIGHT FIELD CAMERAS or PLENOPTIC CAMERAS

- NOT NOW !!!

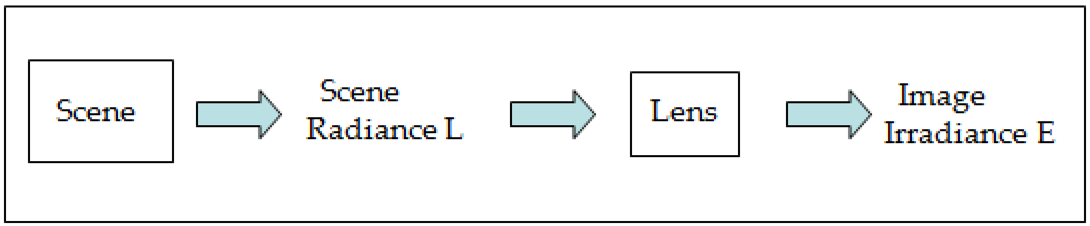
RADIOMETRY & PHOTOMETRY

Image formation



Relationship between scene and image brightness

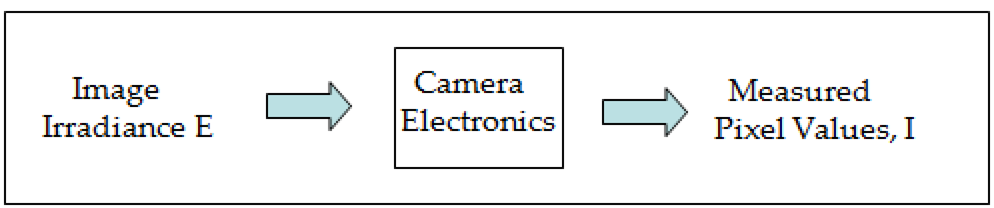
- Before light hits the image plane:



Linear Mapping!

Radiance:
related to
the amount of energy
radiated by a surface

- After light hits the image plane:



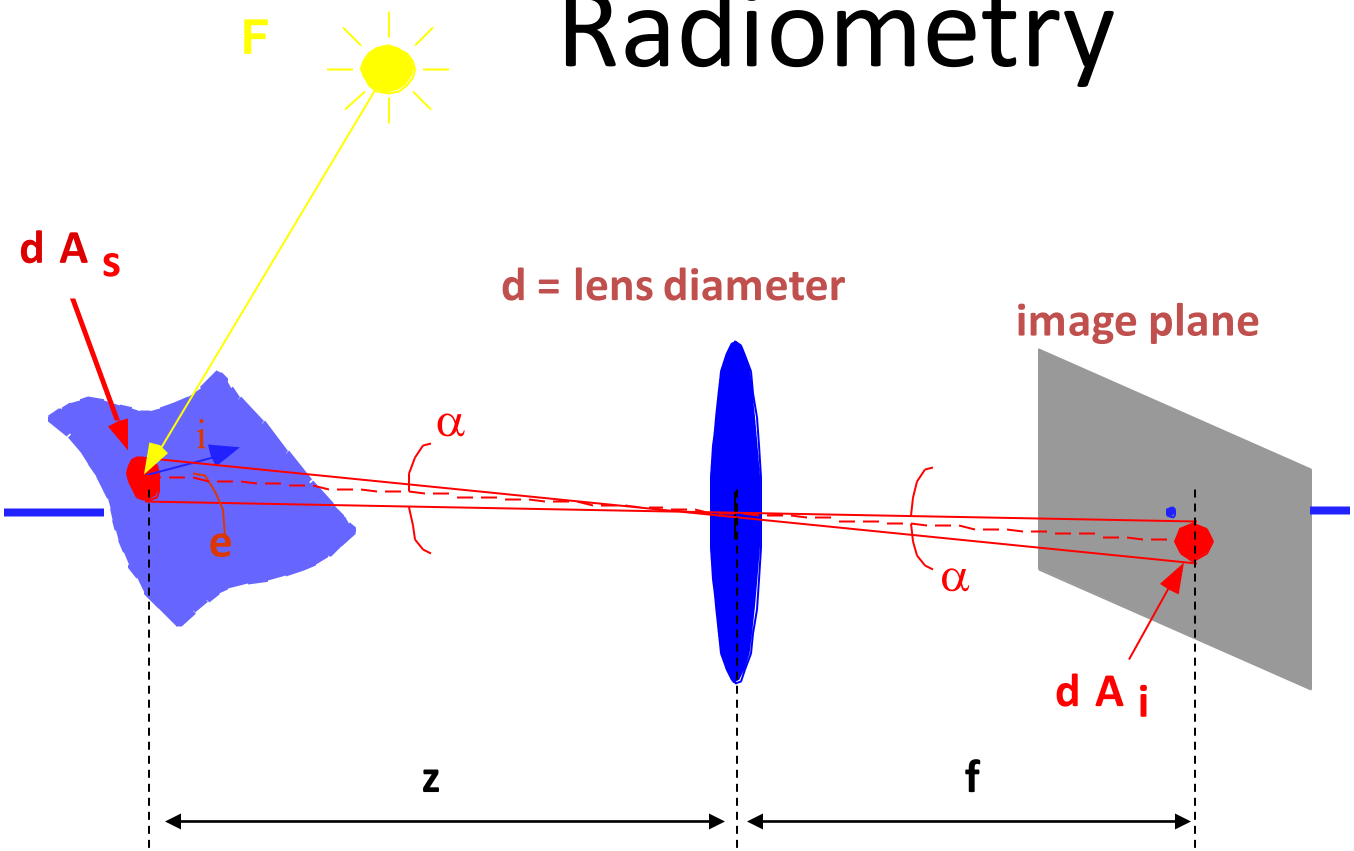
Non-linear Mapping!

Irradiance:
related to
the amount of energy
falling on the image plane

Brightness:

informal concept used to describe both scene brigthness and image brightness

Radiometry

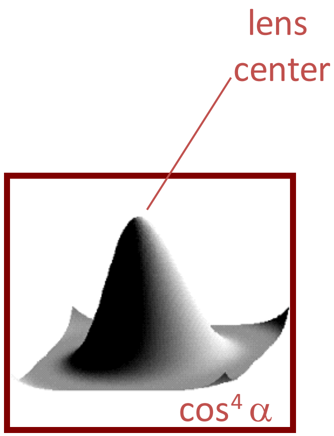


$$E_i = L_s \frac{\pi}{4}\left(\frac{d}{f}\right)^2 \cos^4 \alpha$$

Image irradiance equation

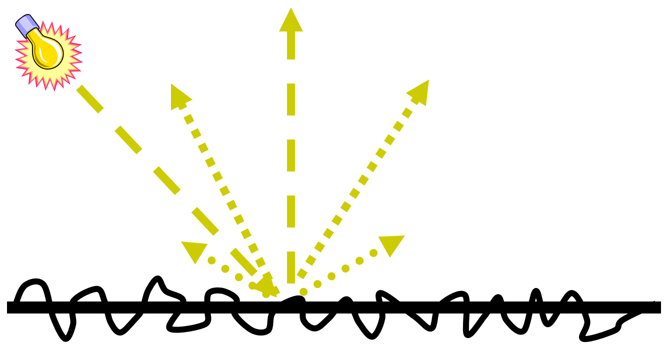
Image irradiance (E_i) is proportional to:

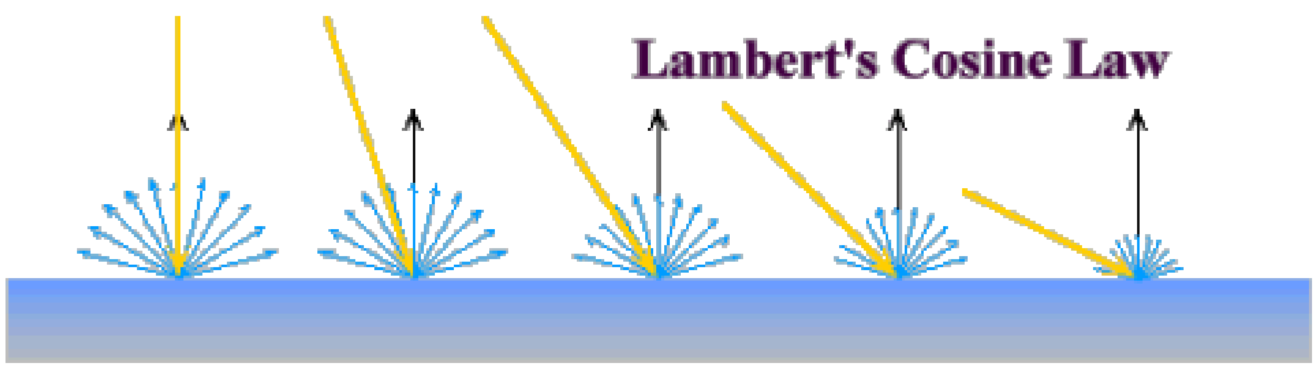
- L_s – scene radiance
- f – focal distance of the lens
- d – diameter of the lens
    - f/d = f-number of the lens
- α - angle to the optical axis



Diffuse (Lambertian) reflection

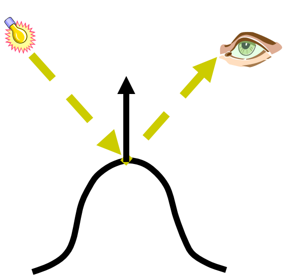
- When the surface is very rough
  light is reflected equally in all directions
  - Surface appears equally bright from ALL directions!

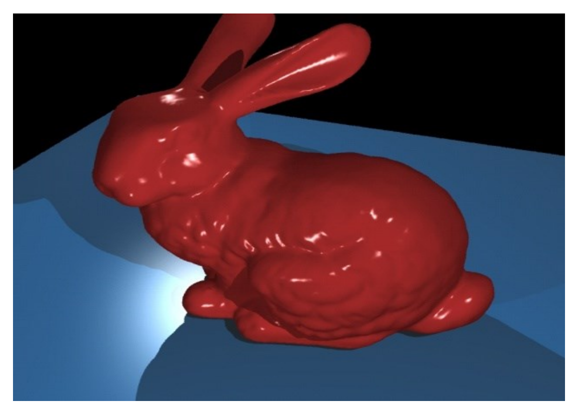


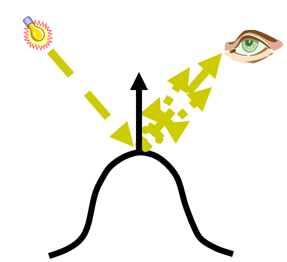


Specular reflection

- Specular reflection is the mirror-like reflection of light.
- Light from a single incoming direction (a ray) is reflected to a single outgoing direction.
- The direction of incoming light (the incident ray), and the direction of outgoing reflected light (the reflected ray) make the same angle with respect to the surface normal (the angle of incidence equals the angle of reflection)
- The presence of specular reflections in images can lead many computer vision algorithms to produce erroneous results.





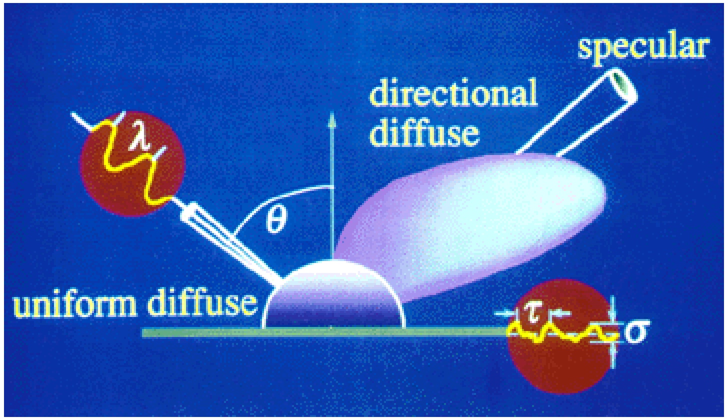


Phong's model

- Reflectance is modeled using 3 components:
  - ambient
  - diffuse
  - specular

$$I_e = k_a I_a + I_i \left[k_d (\mathbf{N} \cdot \mathbf{L})_+ + k_s (\mathbf{V} \cdot \mathbf{R})_+^{n_s} \right]$$

L, **N**, **V** unit vectors
I_i = incident radiance
I_e = reflected radiance
I_a = ambient light
k_a = ambient light reflection factor
$(x)_+ = \max(x, 0)$



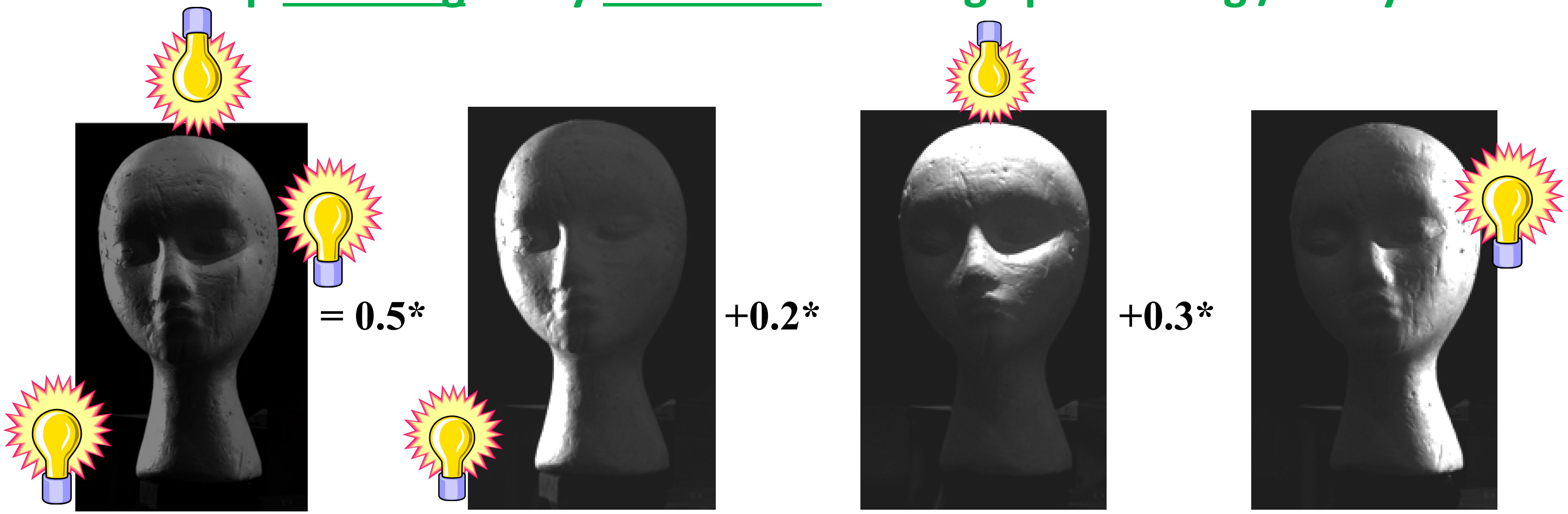
- *There are more realistic models (ex: Torrence-Sparrow)*

The 4 cornerstones of vision illumination

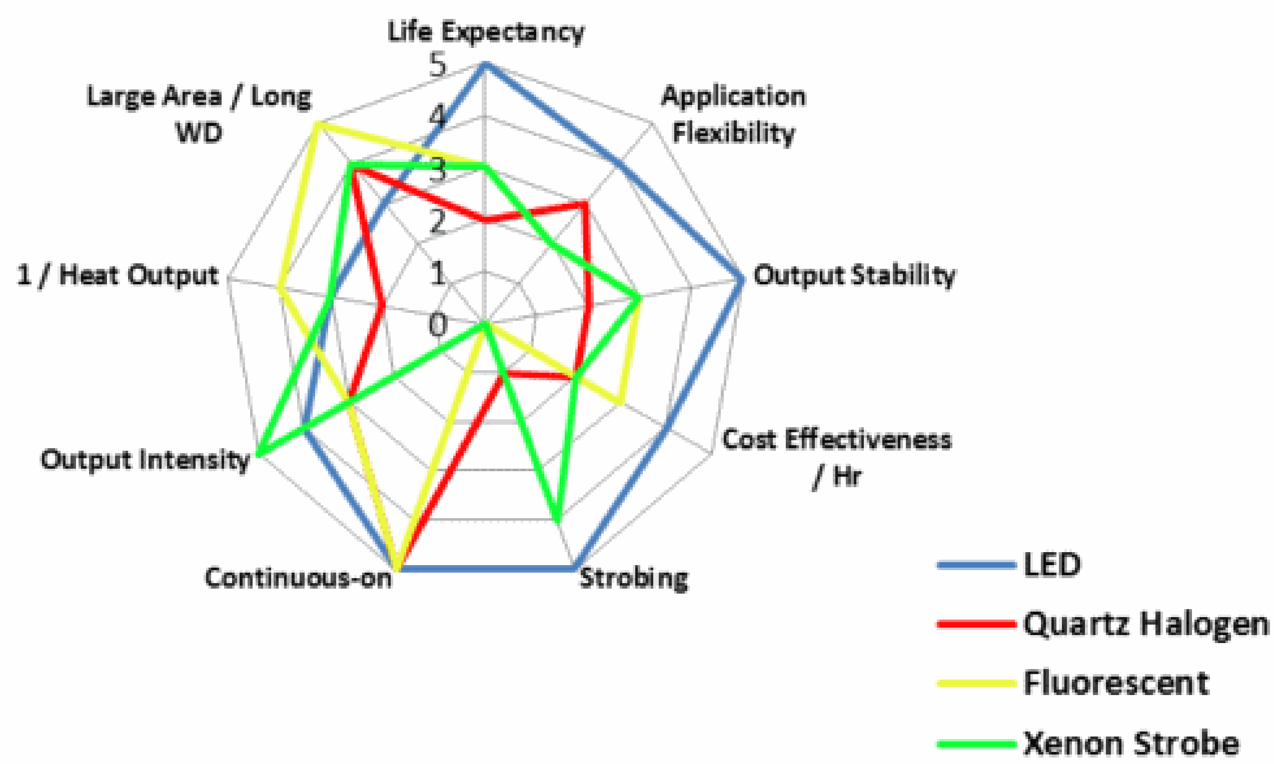
- Geometry
  - The 3-D spatial relationship among sample/object, light and camera
- Structure or Pattern
  - The shape of the light projected onto the sample
- Wavelength or Color
  - How the light is differentially reflected or absorbed by the sample and its immediate background
- Filters
  - Differentially blocking and passing wavelengths and/or light directions

Illumination

- Illumination may introduce complexity in the acquired images
  - position of the light source; many degrees of freedom
  - intensity
  - wavelength
- **An adequate control of the illumination can help reducing many difficulties in image processing / analysis**



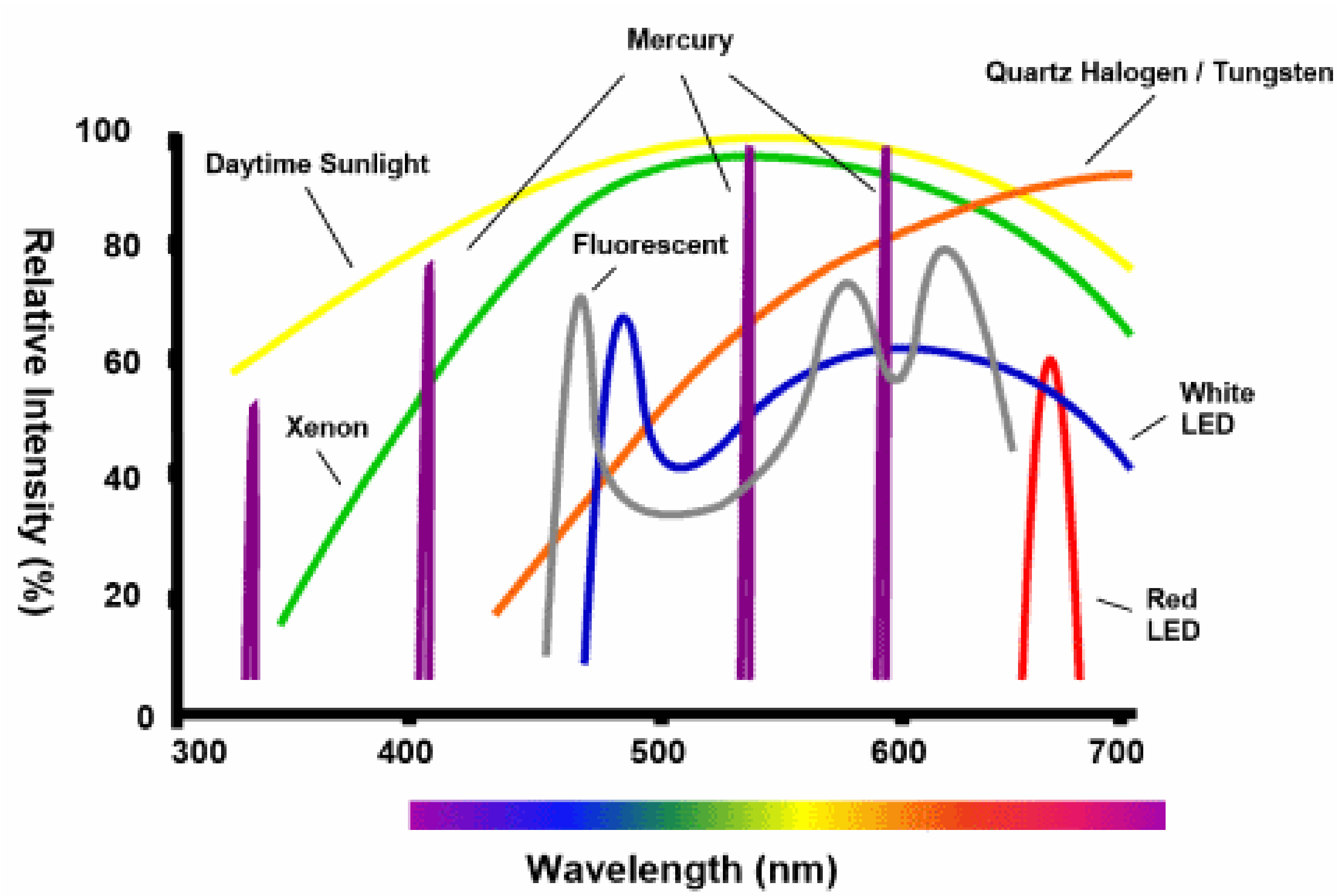
Light sources



Comparison of computer vision light sources

http://www.ni.com/white-paper/6901/en/

Light Source Relative Intensity versus Spectral Content



Light Source Relative Intensity Versus Spectral Content
(The bar at the bottom denotes the approximate human visible wavelength range.)

Considerations for an optimal lighting solution

- Inspection environment
- Ambient light contribution
- Sample composition and transmittance
- Sample/Light interactions
- Color analysis

Inspection environment

- Fully understanding the inspection area's
physical requirements and limitations, in a 3D space, is critical.
- In particular, depending on the specific inspection requirements,
the use of robotic pick-and-place machines or pre-existing,
but necessary, support structures,
may severely limit the choice of effective lighting solutions
by forcing a compromise in not only the type of lighting
but also its geometry, working distance, intensity, and pattern.

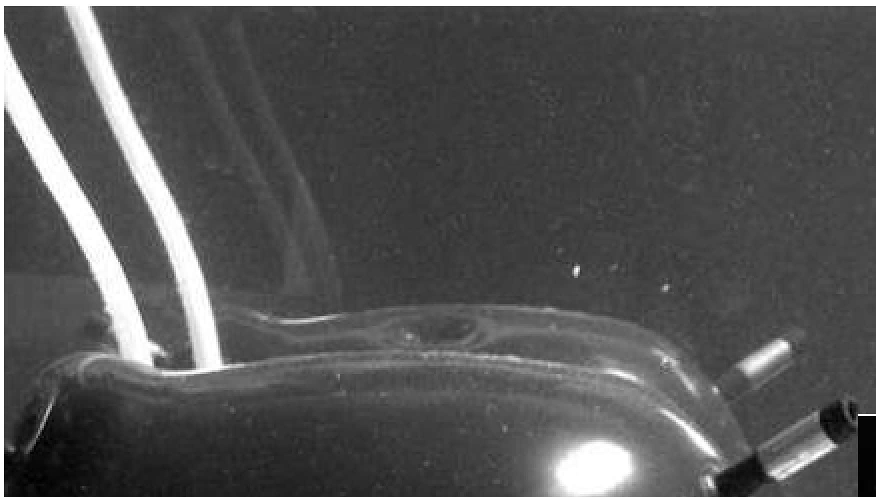
Inspection environment

- Background

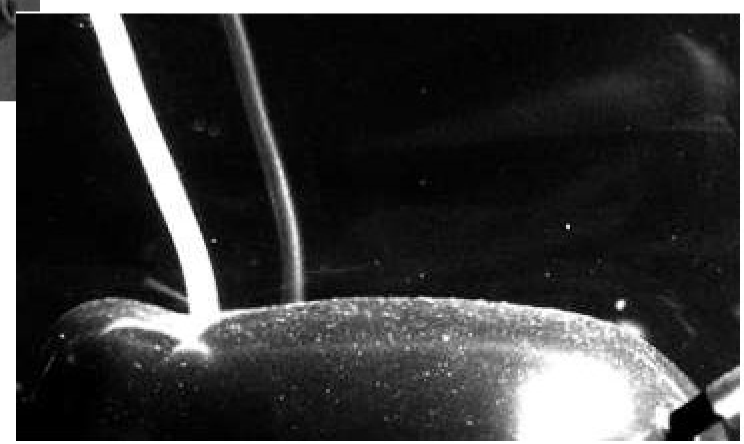
- It is not unusual for the design of a vision system to consider only the object’s appearance and neglect the background’s appearance.
- The background is as much a part of the image as the object.
- If the background is cluttered , the image processing will likely be more complex .
- If the background changes , then the results of image processing might be unpredictable
- A good technique is the “black hole” approach , that is, there is nothing behind the field of view of the camera, for quite a distance.
- (note: light energy falls off as the square of the distance so little energy from the bottom of the “black hole” will reach the camera).

Inspection environment

- Background



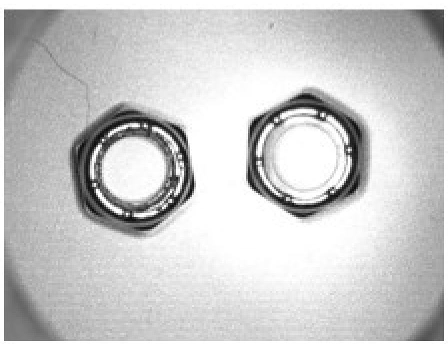
Reflective background

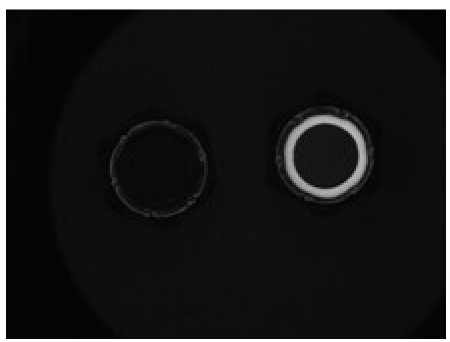


Back background

Ambient light contribution

- The presence of ambient light
can have a tremendous impact on
the quality and consistency of inspections,
particularly when using a multispectral source such as white light.



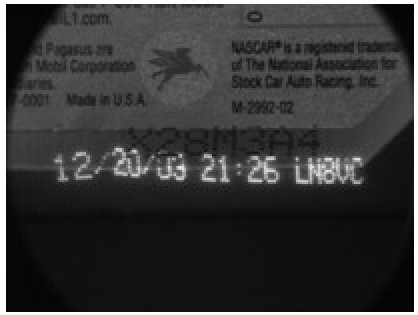


The left image shows nyloc nuts with a UV ring light, but flooded with red 660 nm "ambient" light. The goal is to determine nylon presence/absence. Given the large ambient contribution, it is difficult to get sufficient contrast from the relatively low-yield blue fluoresced light from the sample. The right image has the same lighting, except a 510 nm short pass filter was installed on the camera lens, effectively blocking the red "ambient" light and allowing the blue 450 nm light to pass.

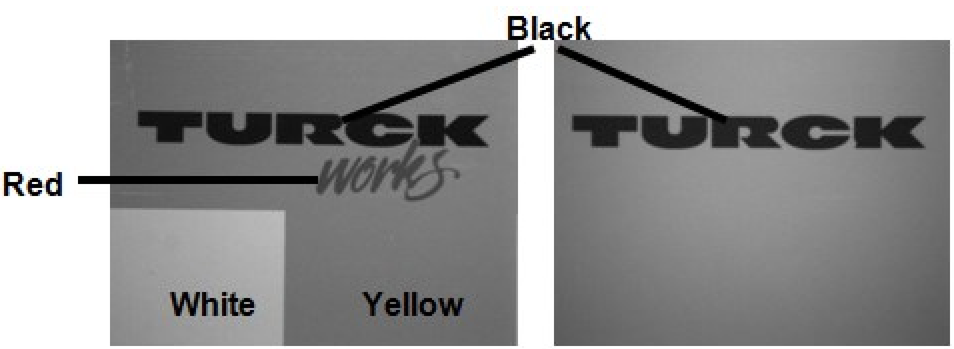
Sample/Light interactions

On the left, the bottom of a soda can is illuminated with a bright field ring light but shows poor contrast, uneven lighting, and specular reflections.
On the right, the soda can is imaged with diffuse light, creating an even background so the code can be read.

Sample Composition and Transmittance



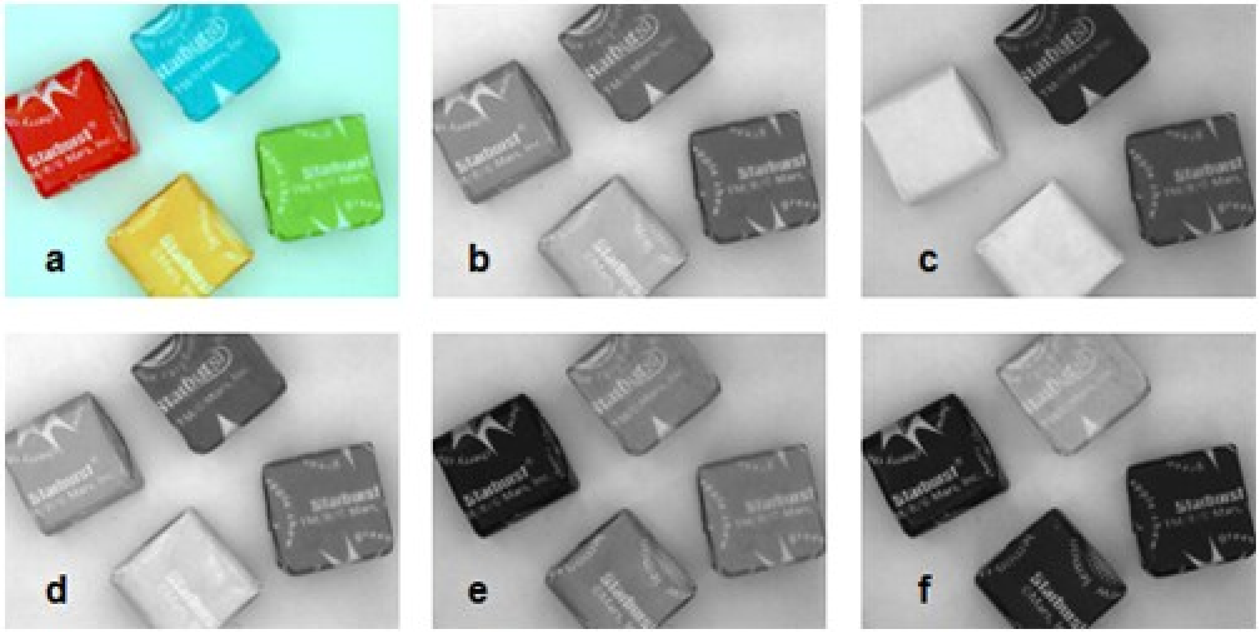
The motor oil bottle on the left is illuminated with a red 660 nm ring light. On the right, the bottle is illuminated with a 360 nm UV fluorescent light.



On the left, the glossy paper sample is under diffuse white light.

The right is under diffuse IR light.

Color analysis



Candy pieces are imaged under

(a) white light and a color CCD camera,

(b) white light and a black and white camera,

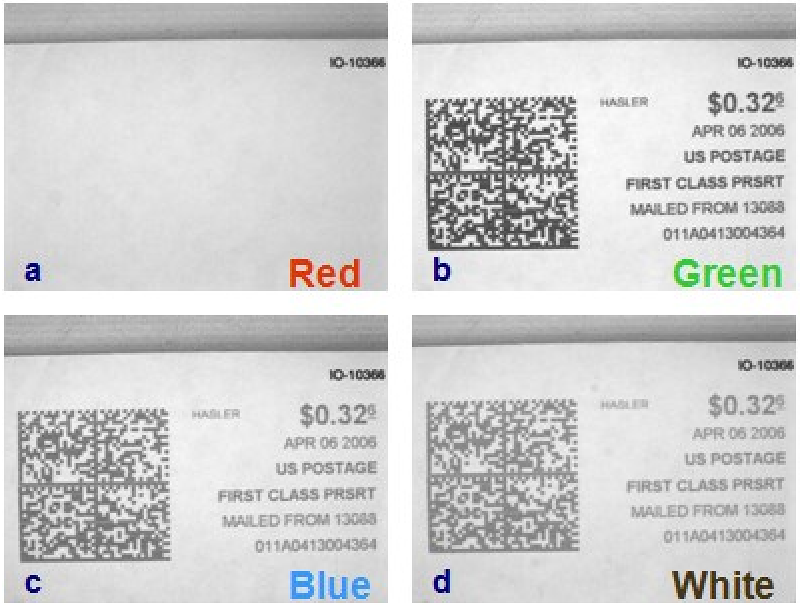
(c) red light, lightening both the red and yellow and darkening the blue,

(d) red and green light, yielding yellow, lightening the yellow more than the red,

(e) green light, lightening the green and blue and darkening the red,

(f) blue light, lightening the blue and darkening the others

Color analysis

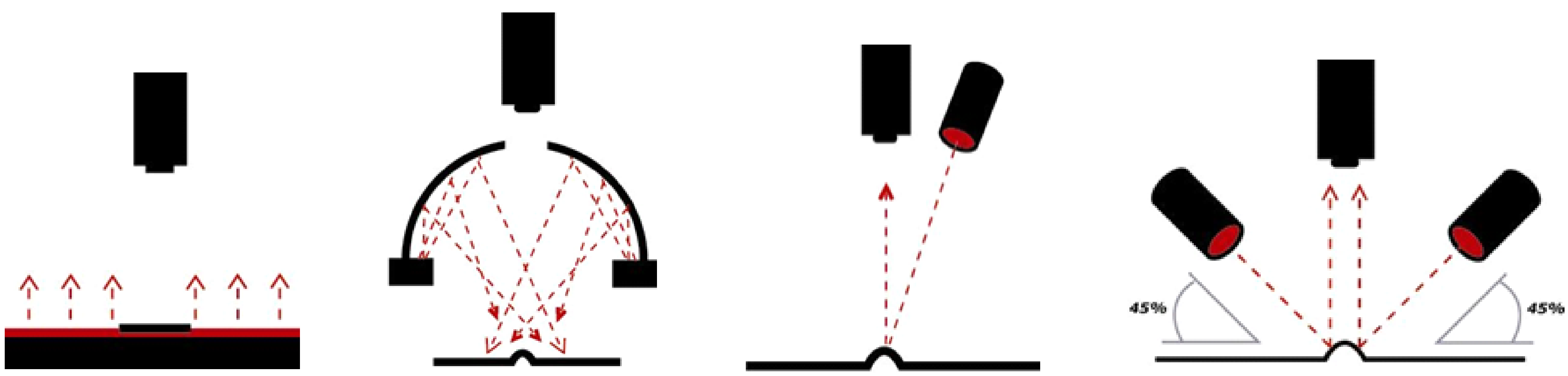


A mail stamp imaged under
(a) red light,
(b) green light,
(c) blue light, generating less contrast than green,
(d) white light, generating less contrast than either blue or green.

White light contrasts all colors, but it may be a contrast compromise.

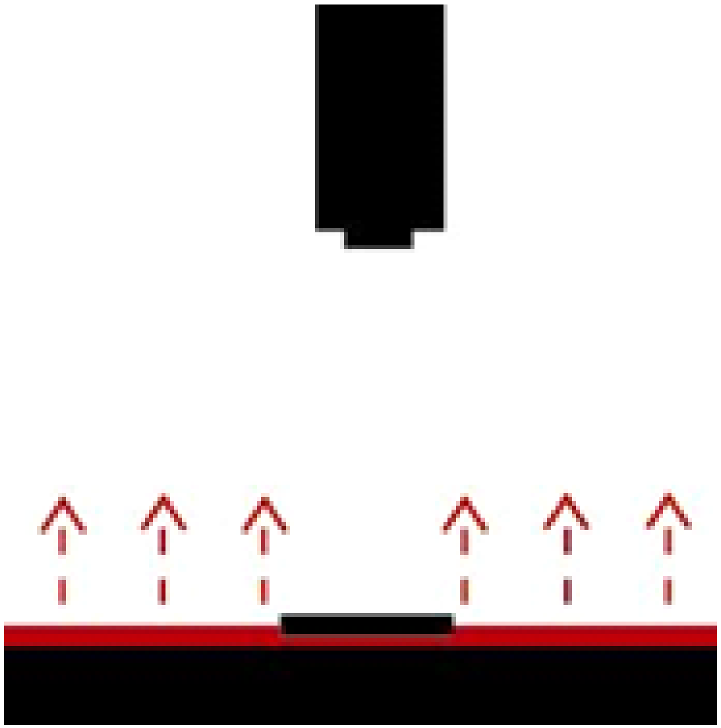
Illumination techniques

- Back lighting
- Diffuse (full bright field) lighting
- Partial bright field or birectional bighting
- Dark field lighting



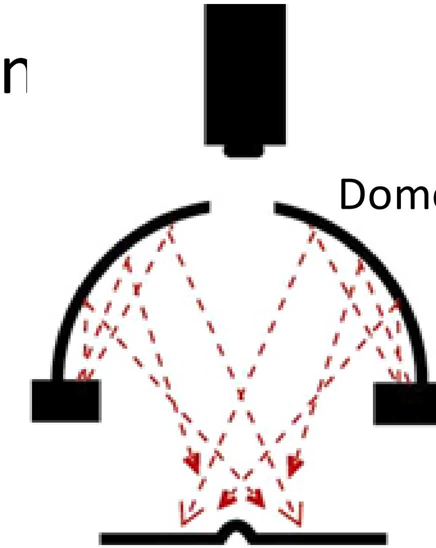
Illumination techniques: back lighting

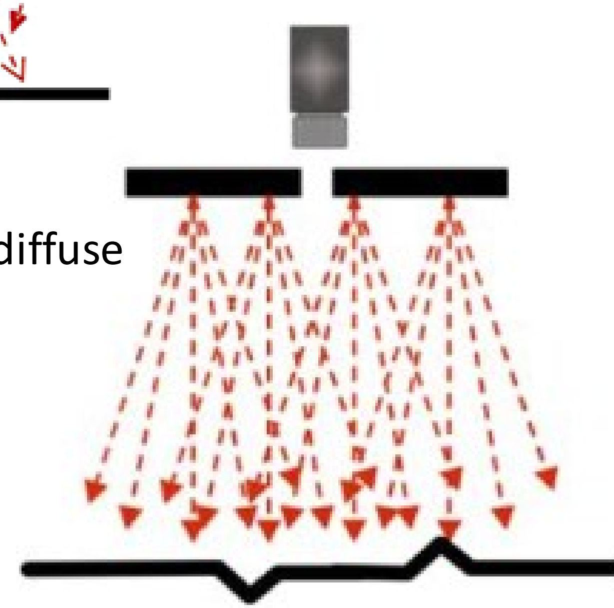
- generates instant contrast as it creates dark silhouettes against a bright background



Illumination techniques: diffuse (full bright field) lighting

- most commonly used on shiny specular or mixed reflectivity samples where even but multidirectional light is needed
  - <u>effective</u> at lighting <u>curved, specular surfaces</u>, commonly found in the automotive industry, for example

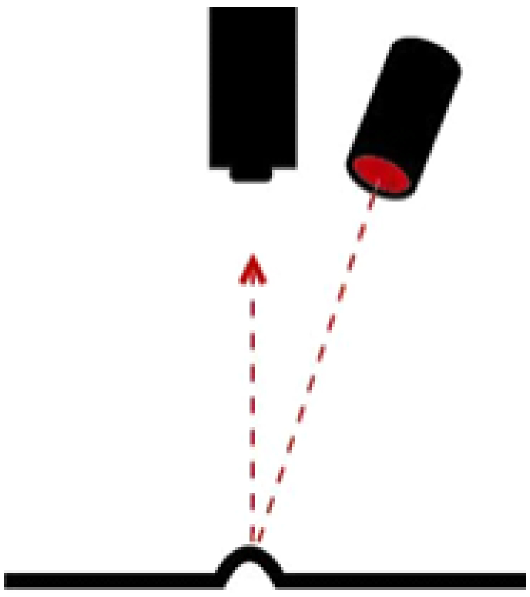




Illumination techniques: partial bright field or directional lighting

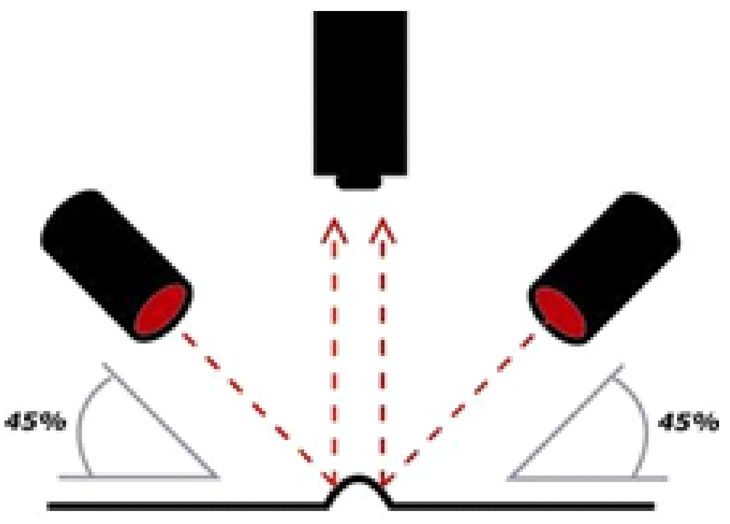
– is the most commonly used vision lighting technique, and is the most familiar lighting used every day, including sunlight

- it is a good choice for <u>generating contrast</u> and <u>enhancing topographic detail</u>
- it is much <u>less effective</u>, however when used on-axis <u>with specular surfaces</u>



Illumination techniques: dark field lighting

- is perhaps the least well understood of all the techniques, although you do use these techniques in everyday life
  - for example, the use of automobile headlights relies on light incident at low angles on the road surface, reflecting back from the small surface imperfections, and also nearby objects



Illumination

- The importance of selecting an adequate light source
- Shapes of typical illumination devices

Why is illumination selection important?

The figure on the right shows the inspection of printed images on an aluminum container. Image 1 was obtained with ring illumination, and image 2 was obtained with dome illumination. As you can see, these images clearly show the extreme influence of illumination for print inspection.

Print on aluminum containers

Scattered reflection interferes with the recognition of printed characters.

There are no shadows in the background and printed characters are clearly shown.

Shapes of typical illumination devices (LED illumination)

source: Keyence
cv_academic3_ka.pdf

Sequence of lighting analysis

- Inspection Physical Environment
  - Physical Constraints
    - Access for camera, lens, and lighting in a 3-D space (working volume)
    - The size and shape of the working volume
    - Min and max camera, lighting working distance and field-of-view
  - Part Characteristics
    - Sample stationary or moving?
    - If moving, speeds, feeds, and expected cycle time?
    - Strobing? Expected pulse rate, on-time, and duty cycle?
    - Are there any continuous or shock vibrations?
    - Is the part presented consistently in orientation and position?
    - Any potential for ambient light contamination?
  - Ergonomics and Safety
    - Man-in-the-loop for operator interaction?
    - Safety related to strobing or intense lighting applications?
- Sample/Light Interactions
  - Sample surface
    - Reflectivity—diffuse, specular, or mixed?
    - Overall geometry—flat, curved, or mixed?
    - Texture—smooth, polished, rough, irregular, multiple?
    - Topography—flat, multiple elevations, angles?
    - Light intensity needed?
- Sample/Light Interactions (cont.)
  - Composition and Color
    - Metallic, non-metallic, mixed, polymer?
    - Part color vs. background color
    - Transparent, semi-transparent, or opaque - IR transmission?
    - UV dye, or fluorescent polymer?
  - Light Contamination
    - Ambient contribution from overhead or operator station lighting?
    - Light contamination from another inspection station?
    - Light contamination from the same inspection station?
- Features of Interest
- Applying the Four Cornerstones of Lighting
  - Light—Camera sample geometry issues
  - Light pattern issues
  - Color differences between sample and background
  - Filters for short, long, or band pass applications including polarization
- Lighting Techniques and Types Knowledge
  - Fluorescent versus quartz-halogen vs. LED vs. others
  - Bright field, dark field, diffuse, or back lighting
  - Vision camera and sensor quantum efficiency and spectral range

http://www.ni.com/white-paper/6901/en/

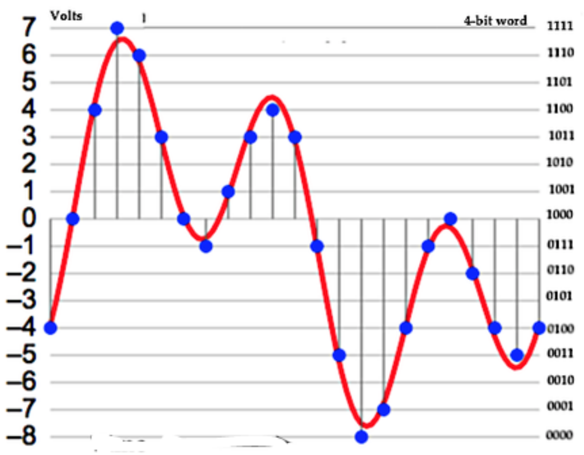
Photometry

- The energy inciding on the sensor (photons) is transformed into an electrical charge by the sensor (**CCD, CMOS**, …)
  - This transformation can be linear or not
  - CCD – highly linear; CMOS – logarithmic
  - CMOS: lower noise at high speeds; used in mobile phone cameras;
- This electrical charge is then transformed into an electronic signal by the electronic circuits of the camera.
- Frequently, those circuits make a correction of the signal (*gamma correction*), in order to compensate for the fact that monitors produce a luminous intensity that is not proportional to the input voltage (*gamma* tipical value of a monitor ≈ 2.5).
- The relationship between the voltage (V) and image irradiance (E) is $\rightarrow V=k \cdot E^{\gamma}$
  - k and γ are constants
  - $\gamma = 1 \rightarrow$ linear relationship
  - $\gamma = 0.45 \rightarrow$ non-linear relationship
    value frequently used to compensate for the *gamma* of the monitor

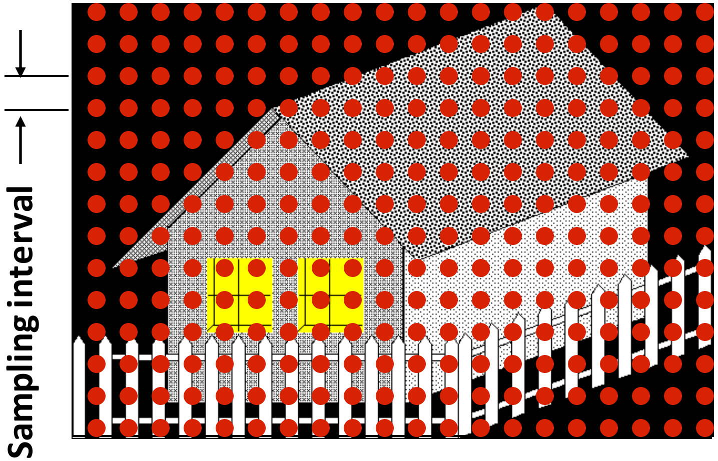
https://www.teledynedalsa.com/imaging/knowledge-center/appnotes/ccd-vs-cmos/
http://www.bberger.net/rwb/gamma.html
http://www.cambridgeincolour.com/

Digitization

- Digitization
  - conversion of a continuous electrical signal into a digital signal (digital image)
- Decisions:
  - Quantification:
    Resolution of the samples
    Sampling grid
    (how the sampled points
    are distributed on the image)
    - rectangular
    - hexagonal
    - …
  - Spatial resolution (how many samples)



Spatial resolution



Coarse sampling: 14 lines; 20 points per line

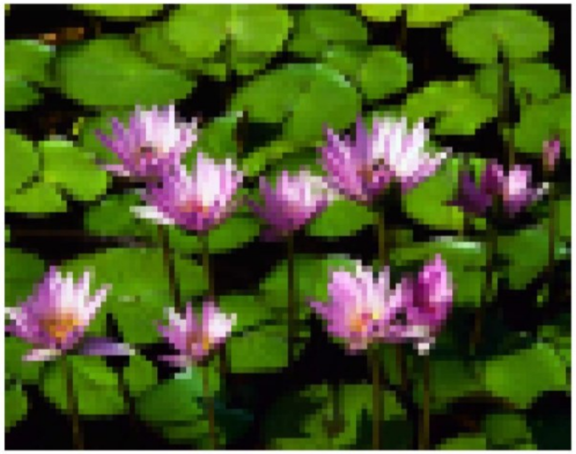
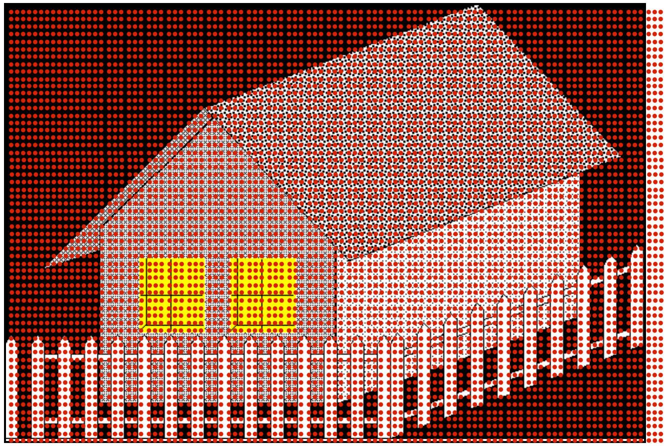


Image w/ resolution of 75x100 *pixels*



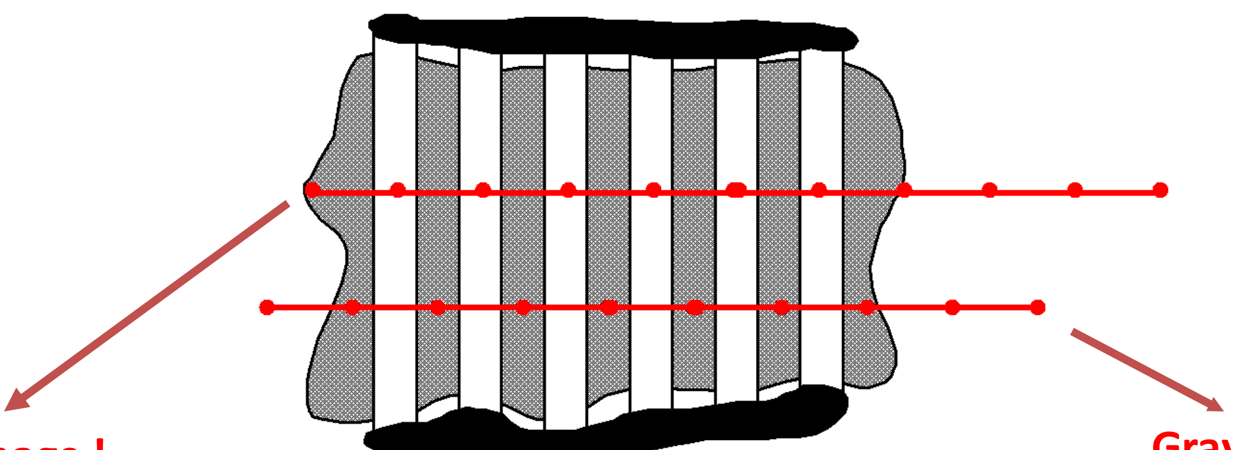
Fine sampling: 68 lines; 100 points per line

Image w/ resolution of 600x800 *pixels*

Effect of the sampling interval

- Analize the neighbourhood of the fence

sampling interval:



White image !

Gray image!

No evidence of the fence !!!

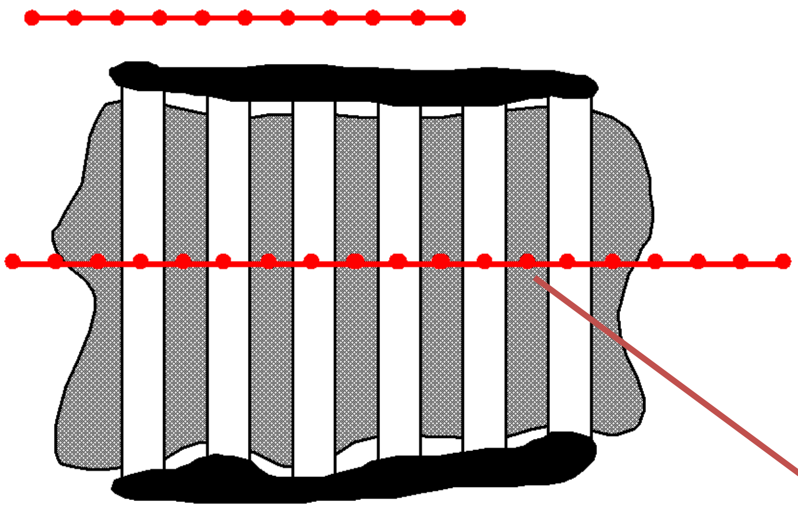
100	100	100	100	100	100
100	100	100	100	100	100
100	100	100	100	100	100
100	100	100	100	100	100

40	40	40	40	40	40
40	40	40	40	40	40
40	40	40	40	40	40
40	40	40	40	40	40

Effect of the sampling interval

- Analize the neighbourhood of the fence

sampling interval:

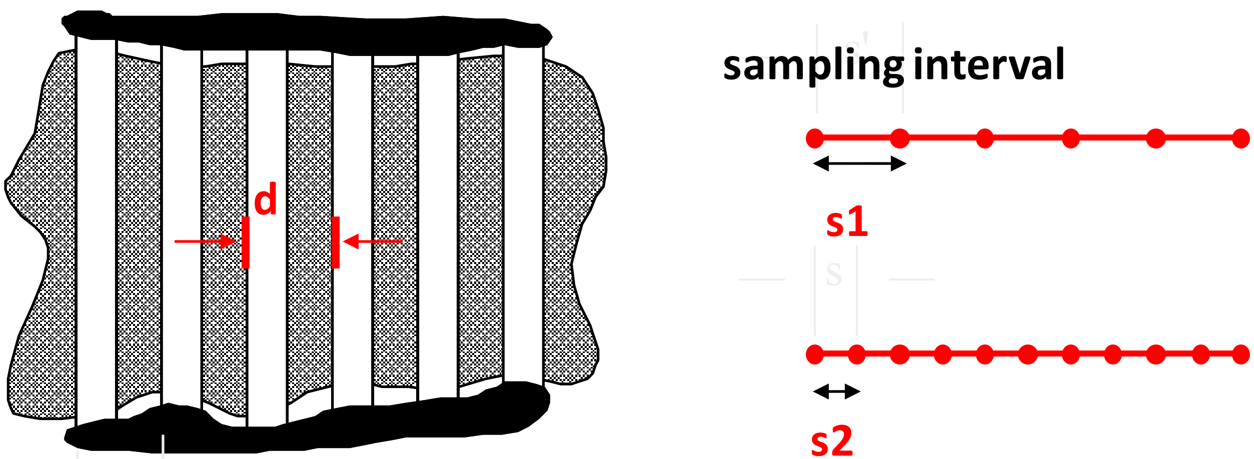


40	100	40	100	40
40	100	40	100	40
40	100	40	100	40
40	100	40	100	40

Now, we can see the fence !
Why ?

Effect of the sampling interval

- The fence has a repetitive structure



Case 1: s1 = d The sampling interval is equal to the size of the repetitive structure **The fence is not seen**

Case 2: s2 = d/2 The sampling interval is equal to 1/2 the size of the repetitive structure **The fence is seen**

SAMPLING THEOREM (Nyquist)
IF the size of the smallest structure that must be preserved is **d**
THEN the sampling interval can't be less than **d/2**

Sampling theorem

- IF
  - the size of the smallest structure that must be preserved is **d**
- THEN
  - the sampling interval can't be less than **d/2**

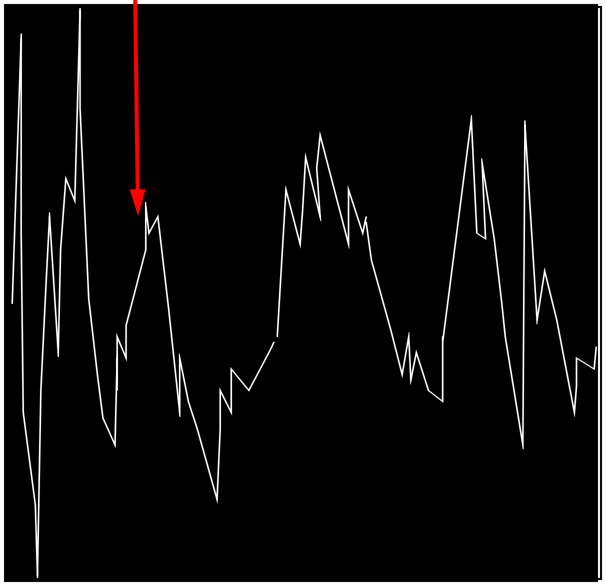
  - The repetitive structure has a certain spatial frequency ("wooden boards/meter" …?).
  - In order to preserve the details of the structure
    one should sample it using a frequency (**Nyquist frequency**)
    that is, at least, the double of that frequency

Quantification

- Objective:
  - to determine the mapping of a continuous signal (analog video signal) into K discrete (digital) levels.

I(x,y) = .1578 volt

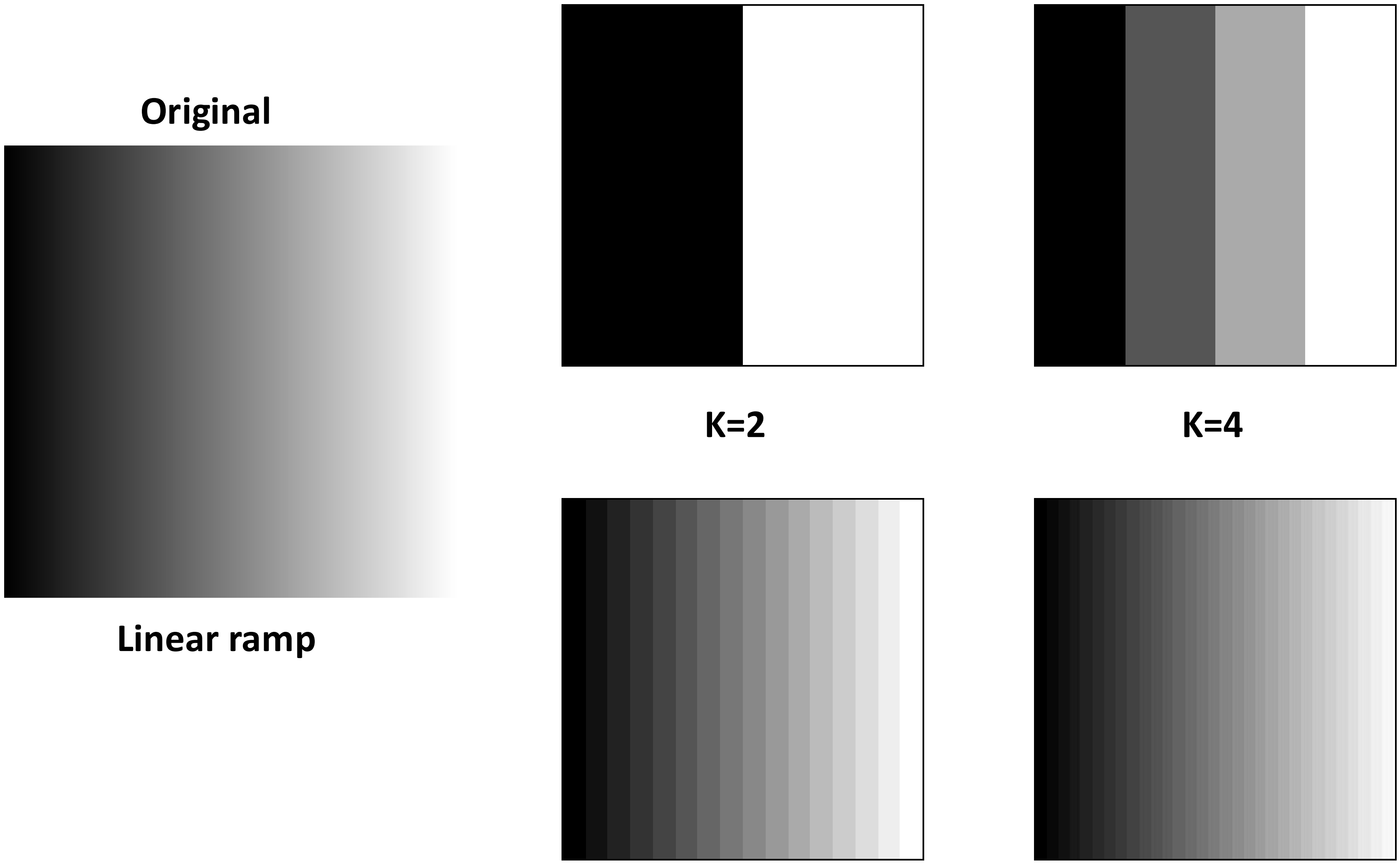
= ???? **(digital value)**



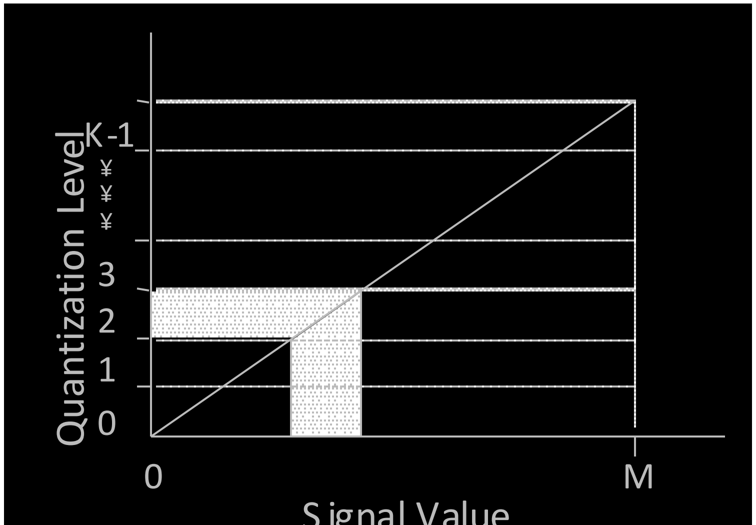
K	#Levels	#Bits
2	2	1
4	4	2
8	8	3
16	16	4
32	32	5
64	64	6
128	128	7
256	256	8

- Several mappings: linear, logarithmic, etc.
- Common value: K=256 (8 *bits*)
  high resolution images $\Rightarrow$ K=1024 ou 4096 *(10 or12 bits)*

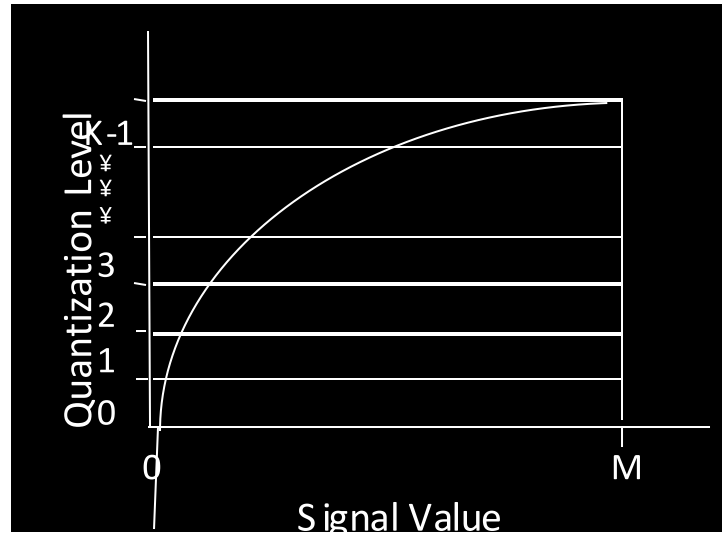
Number of quantification levels



Quantification

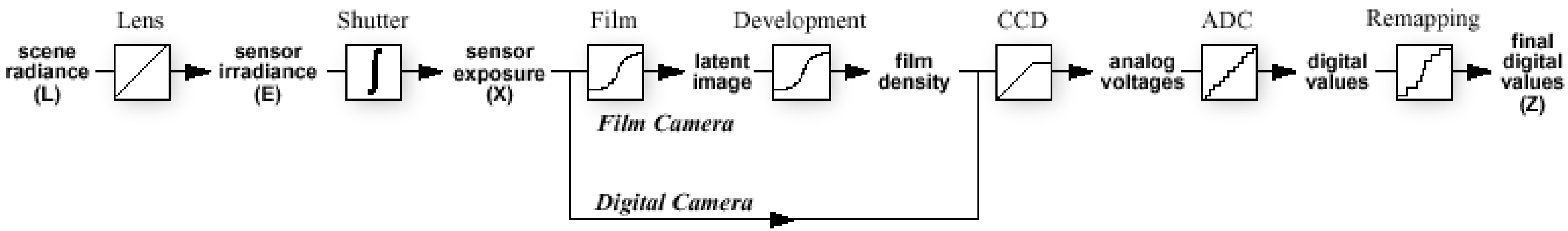


Linear quantification



Logarithmic quantification

Intensity image sensors



- The <u>transfer function of the camera</u>, f(), depends on:
  - aperture
  - shutter speed
  - lens characteristics
  - sensor characteristics (CCD, CMOS, ...)
  - electronic characteristics

- It may be important to determine this function
  - to estimate the properties of the material
  - to implement *shape-from-shading* techniques (*see later*)
  - create images with a high dynamic range (*see later;* Debevec: http://www.debevec.org/Research/HDR)

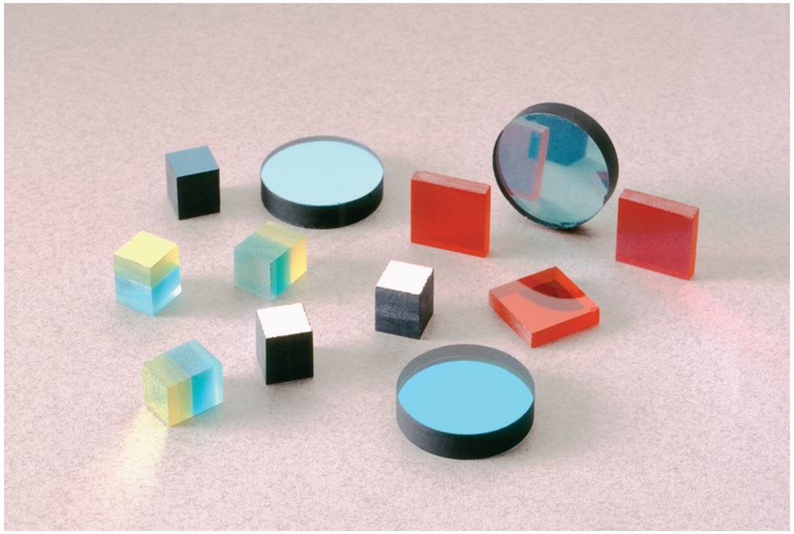
Intensity images: some problems

- Lenses
  - several kind of aberration:
    - geometric distortion, chromatic distortion, …
  - Modulation Transfer Function (MTF) -
    - measures how faithfully the lens reproduces (or transfers) detail from the object to the image produced by the lens (incorporates resolution and contrast into a single specification)
  - vignetting
    - more intensity at the center of the image
- Sensor
  - manufacturing defects
    - defective cells
    - different response to the same light level, … (⇒ adequate calibration when one wants to measure light intensity)
  - saturation
    - automatic gain control may reduce this effect but it may cause other problems
  - *blooming*
    - charge overflow of some cells into neighbour cells (in regions having high intensity);
    - does not occur in CMOS sensors
- Acquisition board (built-in, in digital cameras)
  - effect of the sampling frequency
  - effect of quantification

OPTICS

Optical elements in an imaging system

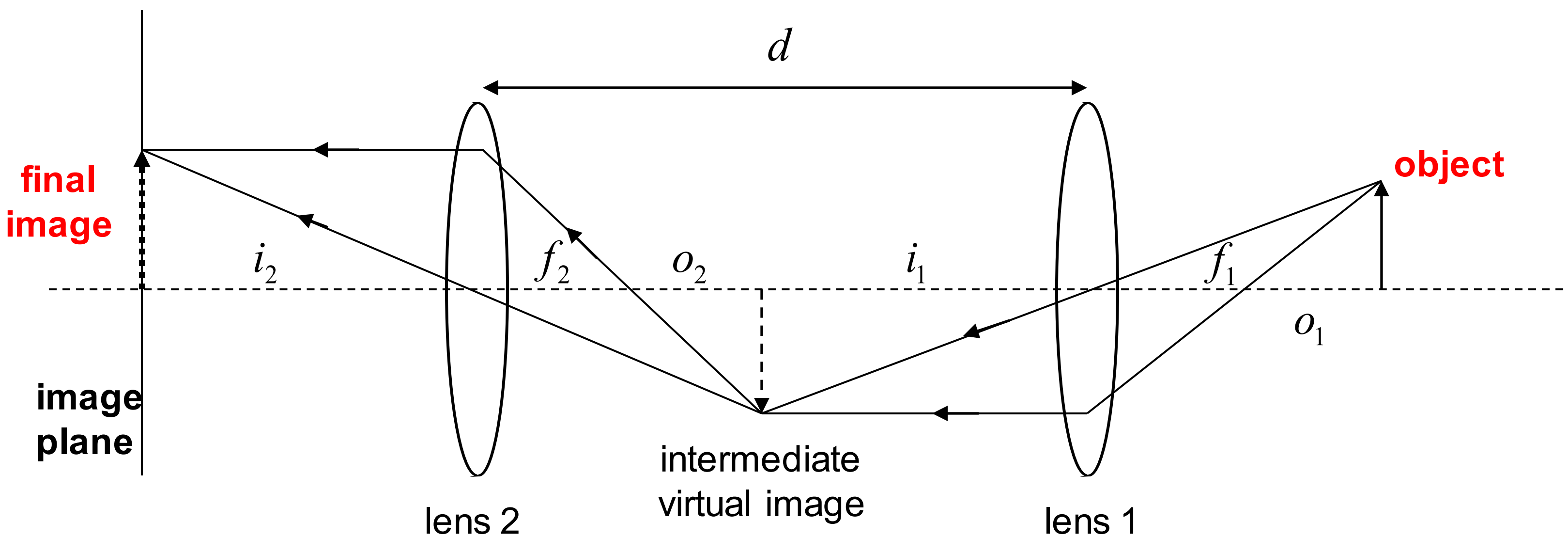
- Lenses
- Filters
- Mirrors
- Prisms



More information:
http://www.edmundoptics.com/technical-resources-center/
http://www.reynardcorp.com/products/optical-components/30-optical-components.html

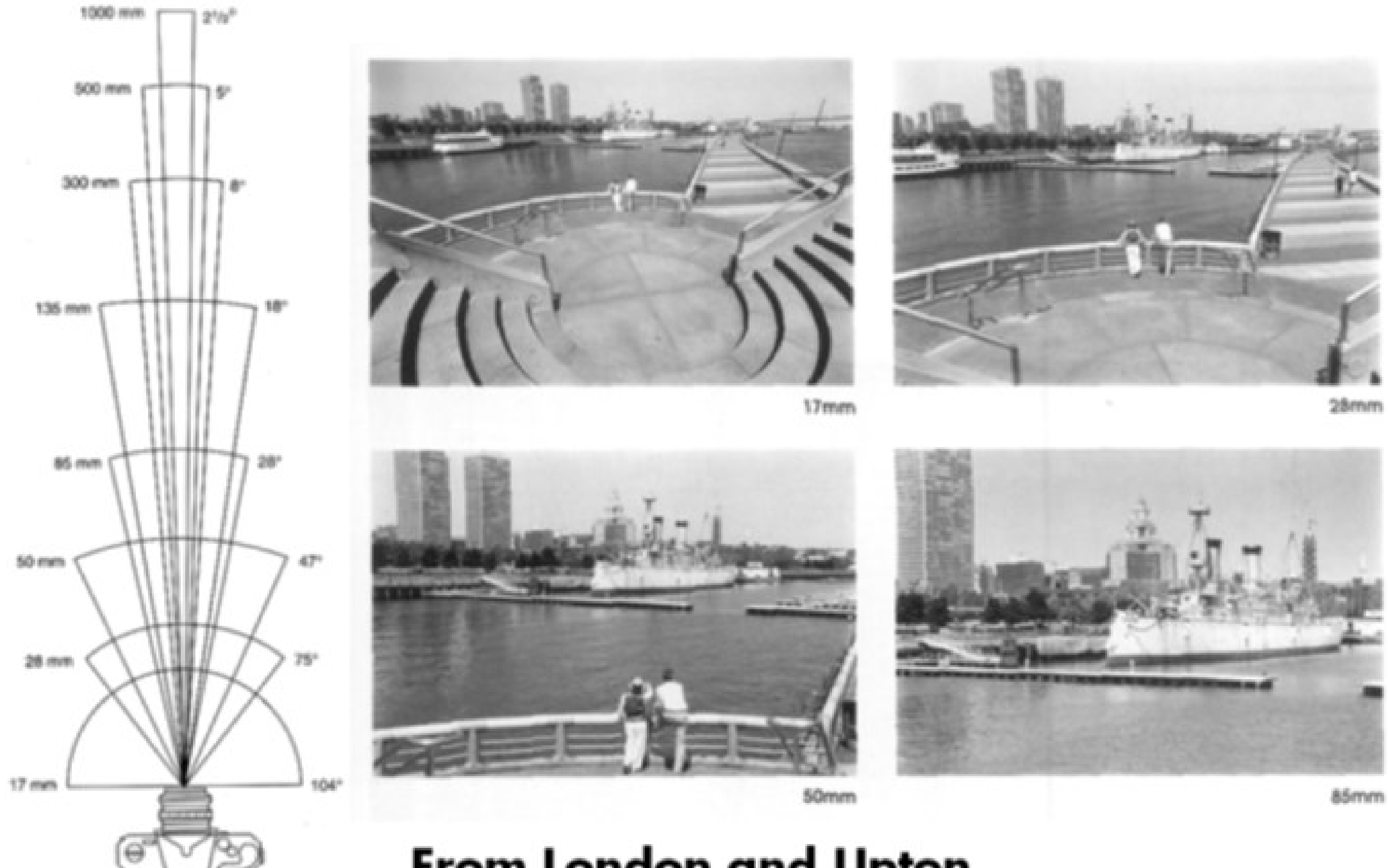
Lenses

- Optics of a two lens system
  - Image formed by first lens is the object for the second lens;
  - Ray passing through focus emerges parallel to optical axis.
  - Ray through optical center passes un-deviated.



Lenses

- Field of view (zoom, focal length)

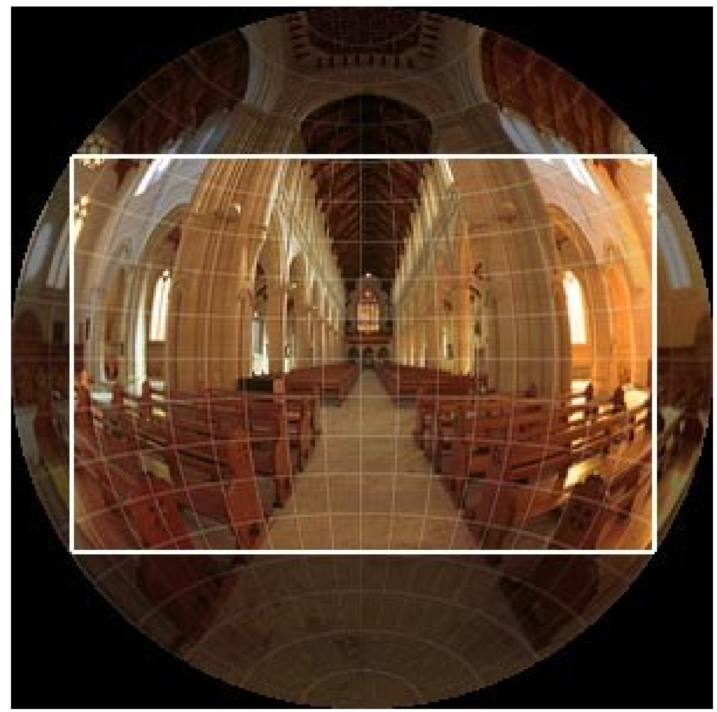


From London and Upton

Lenses

- Wide angle lenses

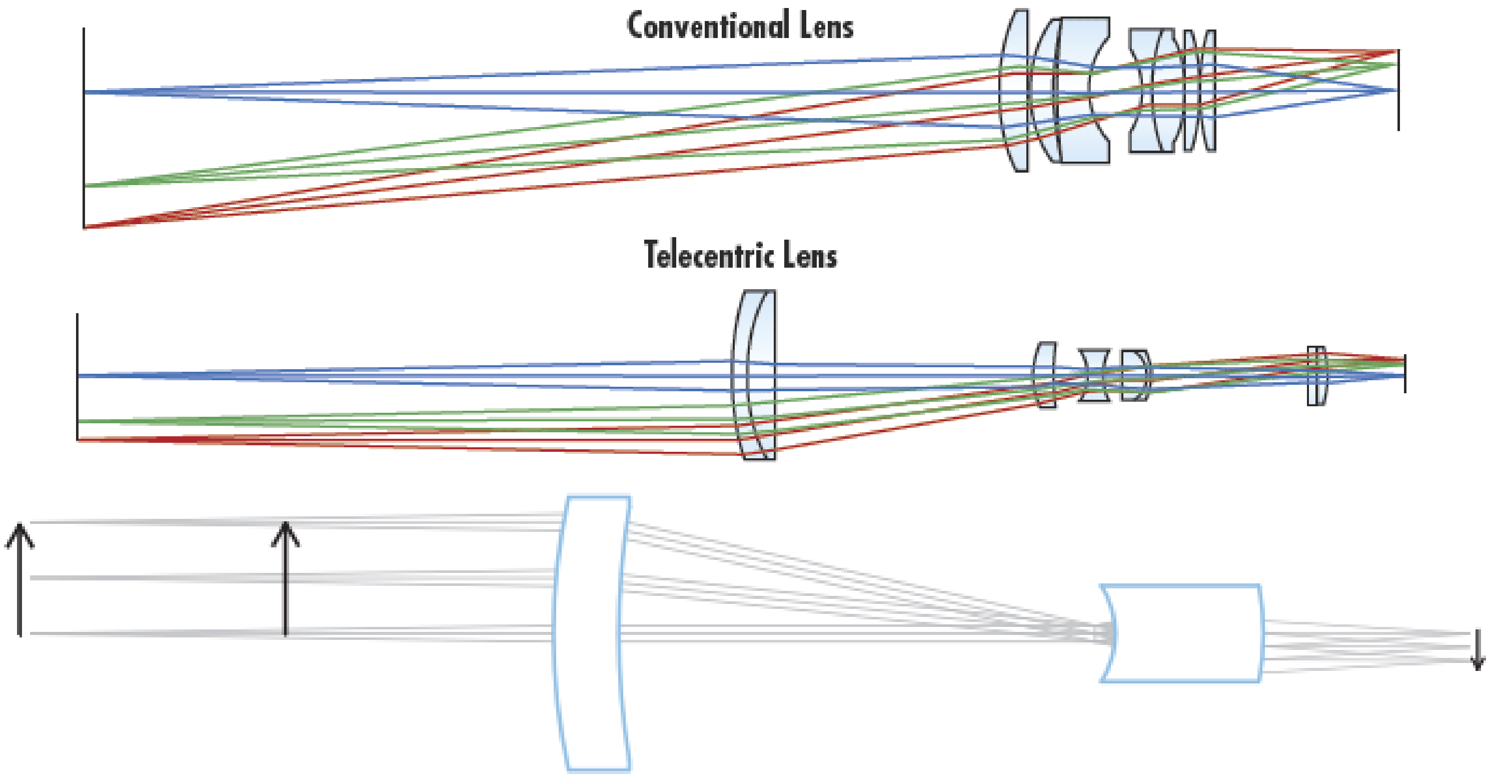
Circular fisheye



Acquired frame

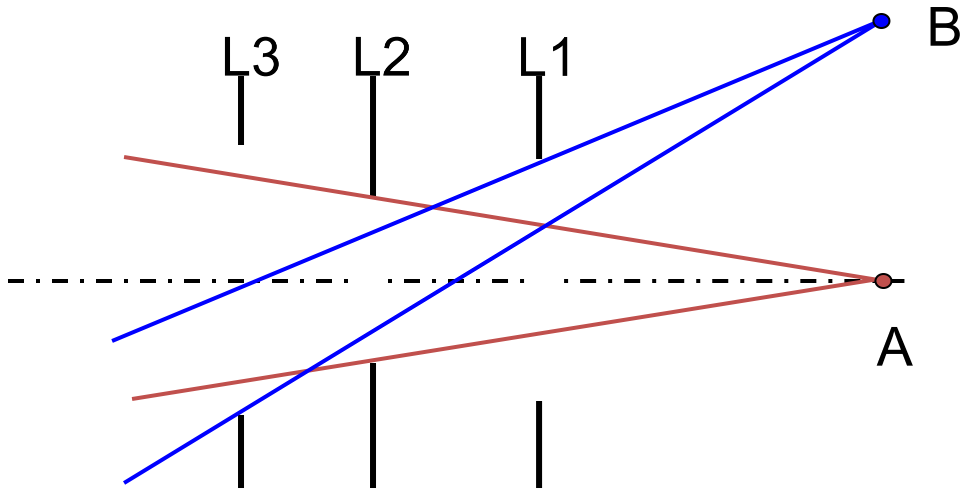
Lenses

- <u>Telecentric lenses</u>
  - Sizes of object and image do not change as they are translated. (eliminate perspective distortion)
  - However, focus does change as in any lens.



Lenses

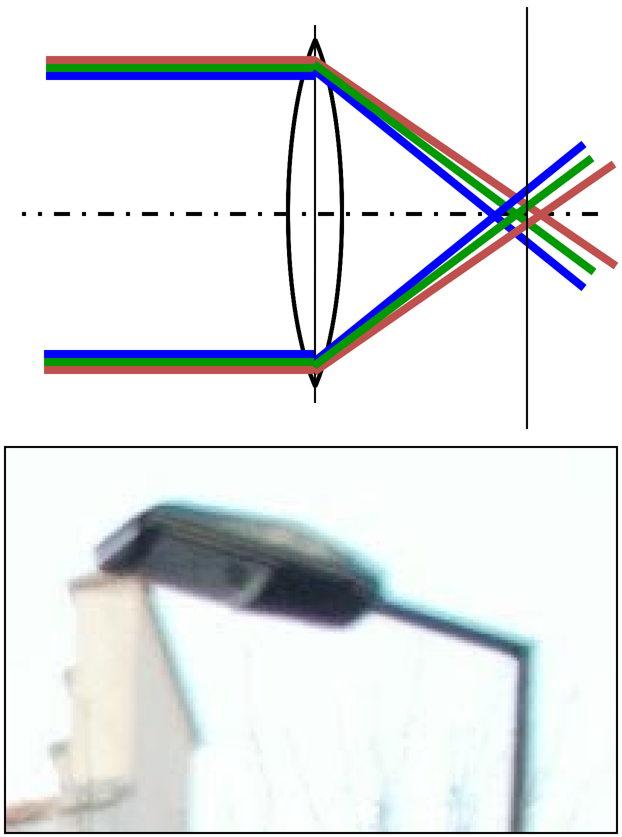
- Common related issues: <u>vignetting</u>



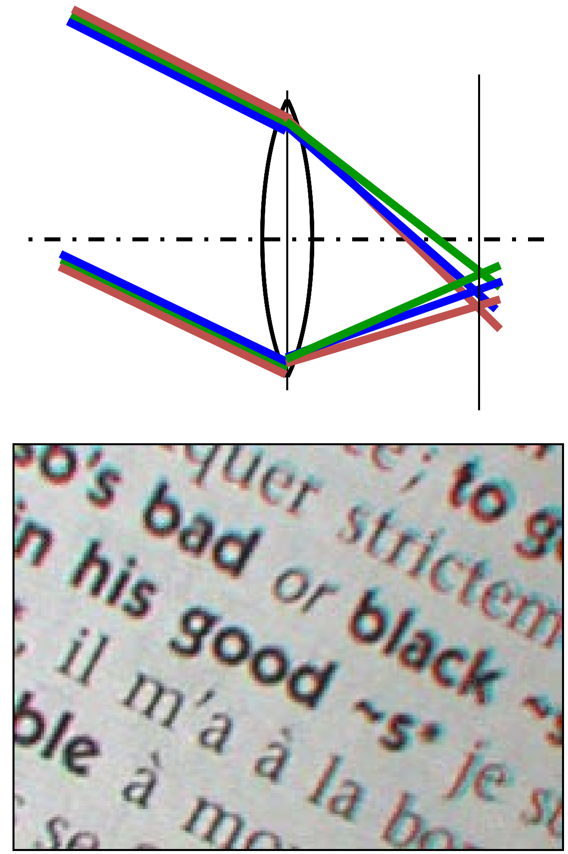
- More light passes through lens L3 for scene point A than scene point B
- Results in spatially non-uniform brightness (in the periphery of the image)

Lenses

- Common related issues: <u>chromatic aberration</u>



Longitudinal chromatic aberration (axial)



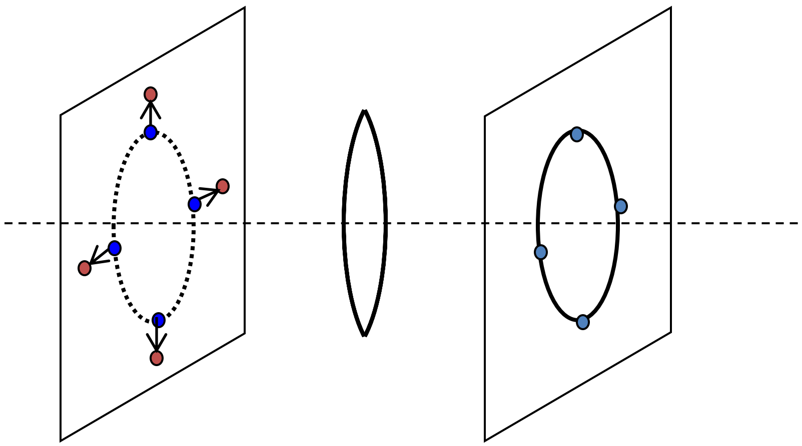
Transverse chromatic aberration (lateral)

Lenses

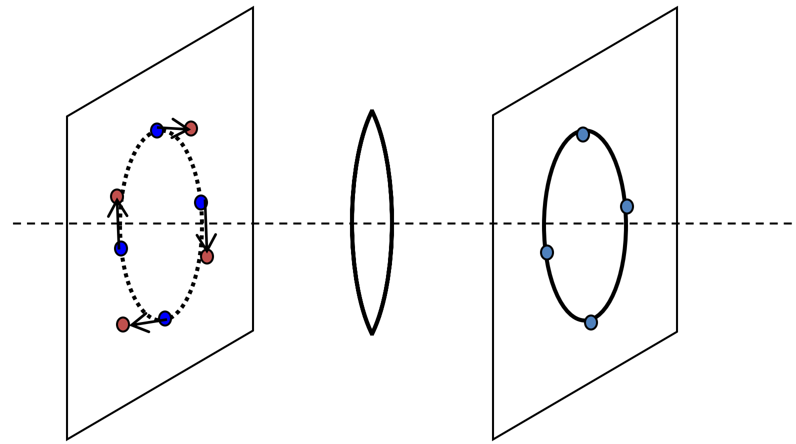
- Common related issues: lens glare
  - Stray interreflections of light within the optical lens system.
  - Happens when very bright sources are present in the scene.

Lenses

- Common related issues: geometric distortion



Radial distortion



Tangential distortion

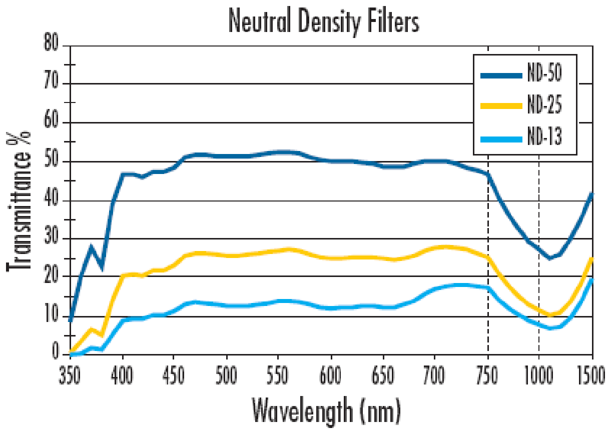
(a) (b) (c)

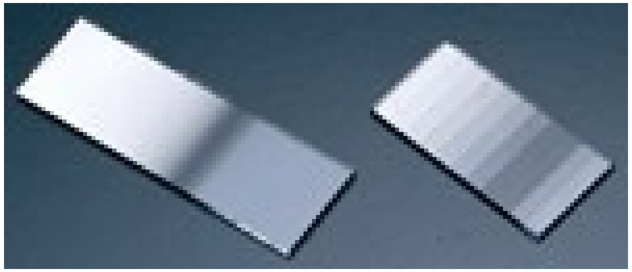
Figure 2.13 Radial lens distortions: (a) barrel, (b) pincushion, and (c) fisheye. The fisheye image spans almost 180° from side-to-side.

Geometric distortion:
- Due to lens imperfection
- Rectify with geometric camera calibration

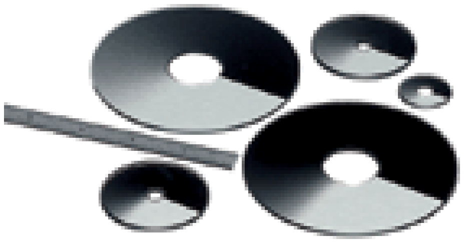
Filters

- Neutral density filters:





Linear variable density

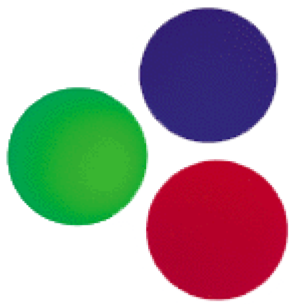
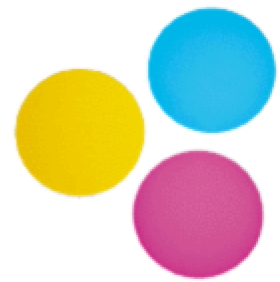
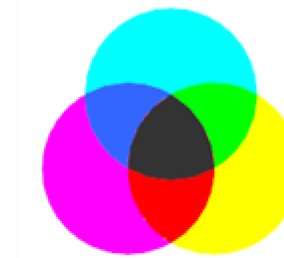
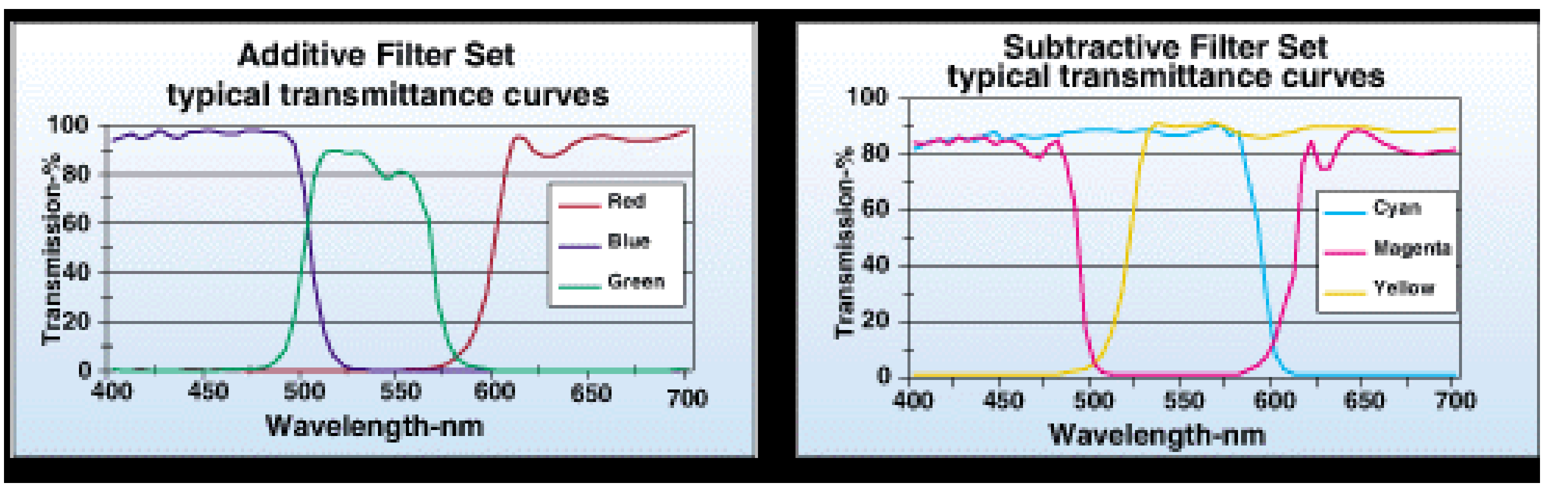


Circular variable density

  - Spectrally flat from 400-700nm
  - Homogeneous glass: blocks by absorption or by reflection
  - Light/Exposure control for imaging

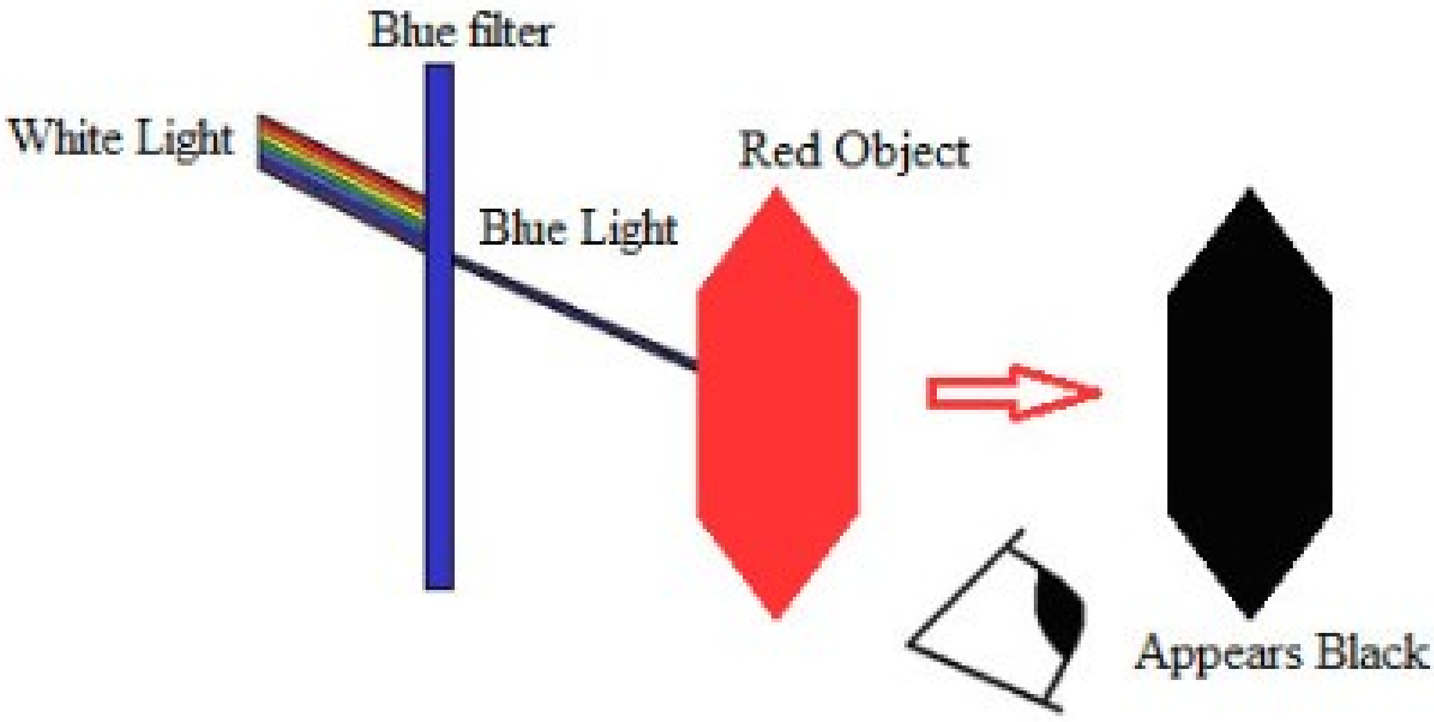
Filters

- Color filters:

Filters

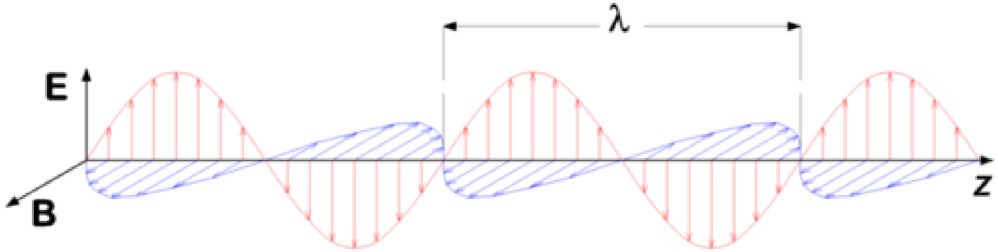
- A color filter is a transparent material that absorbs some colors and allows others to pass through.



SOURCE: http://www.education.com/science-fair/article/colored-lights-effect/

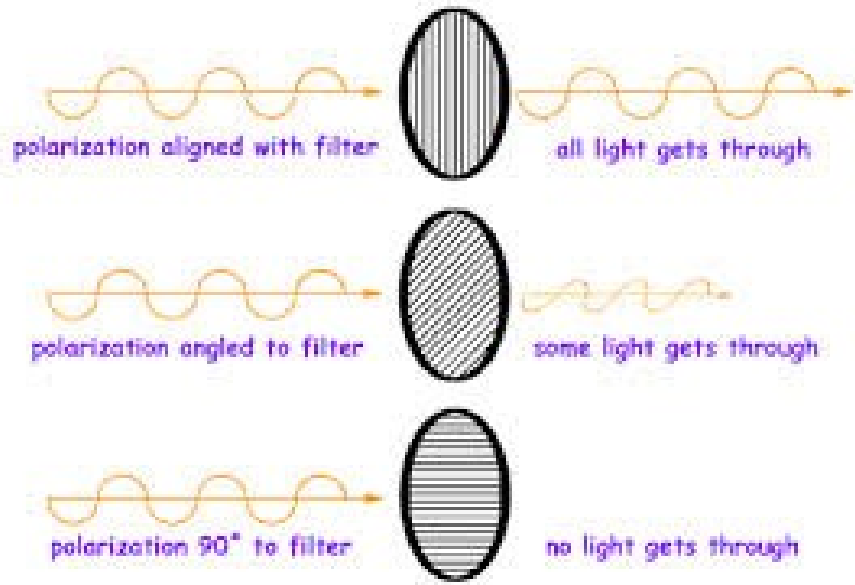
Filters

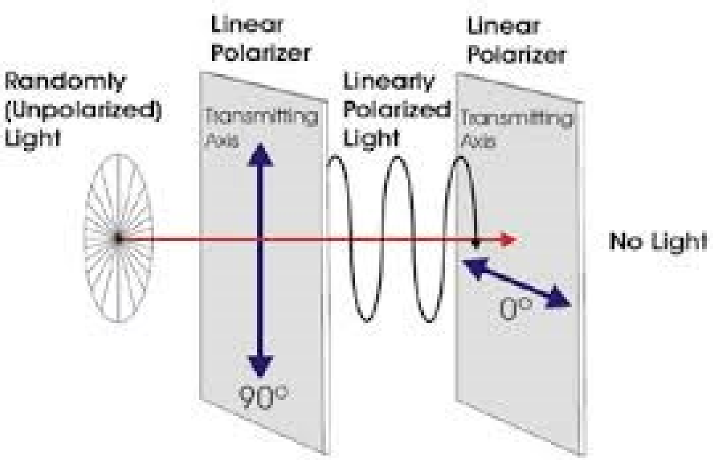
- Polarizing filters:



A "<u>vertically</u> polarized" electromagnetic wave.
λ - wavelength
E (red) - electric field
B (blue) - magnetic field
z - direction of propagation

By convention the "polarization" of light refers to the polarization of the electric field.





Applications of light polarization

Removing specularities

Separating reflected and transmitted scenes

Reconstructing shape of transparent objects

Removing haze and underwater scattering effects

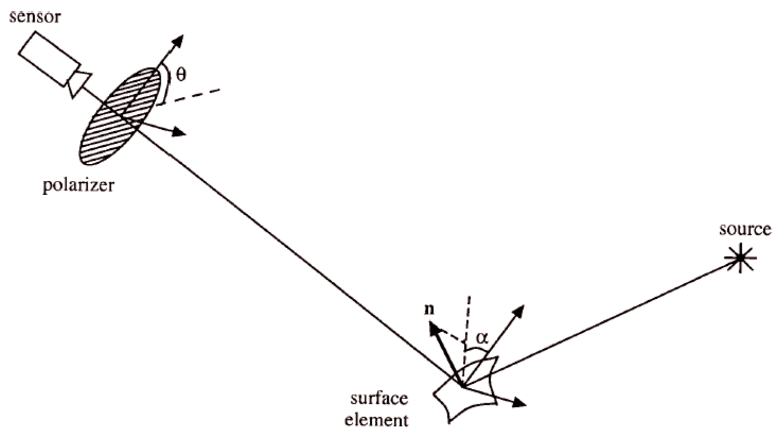
https://www.youtube.com/watch?v=iz6i548ljCE

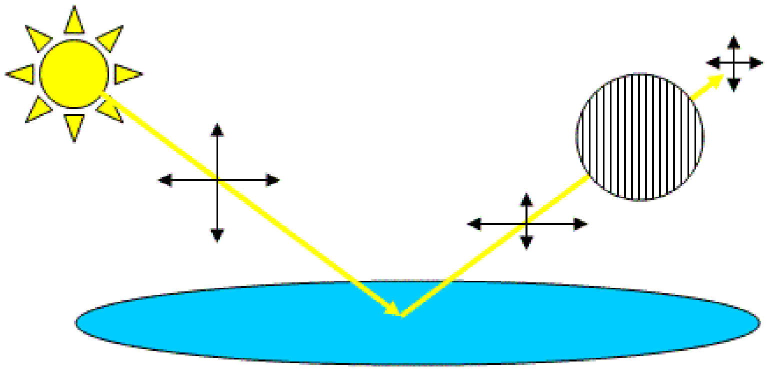
Applications of light polarization

- Separation of diffuse and specular reflections
  - Diffuse surfaces: no (or minimal) polarization
    - All light depolarized due to many random scattering events inside object.
  - Specular Surfaces: strong polarization (even though partially polarized)
  - Smooth/Rough Surfaces: the degree of polarization decreases with roughness.

Applications of light polarization

- Passive Illumination



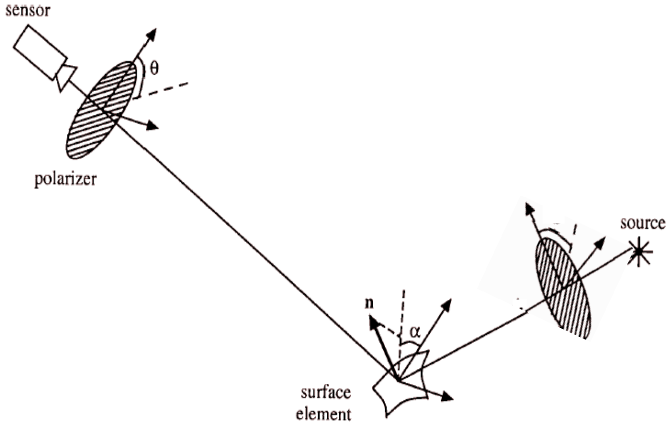


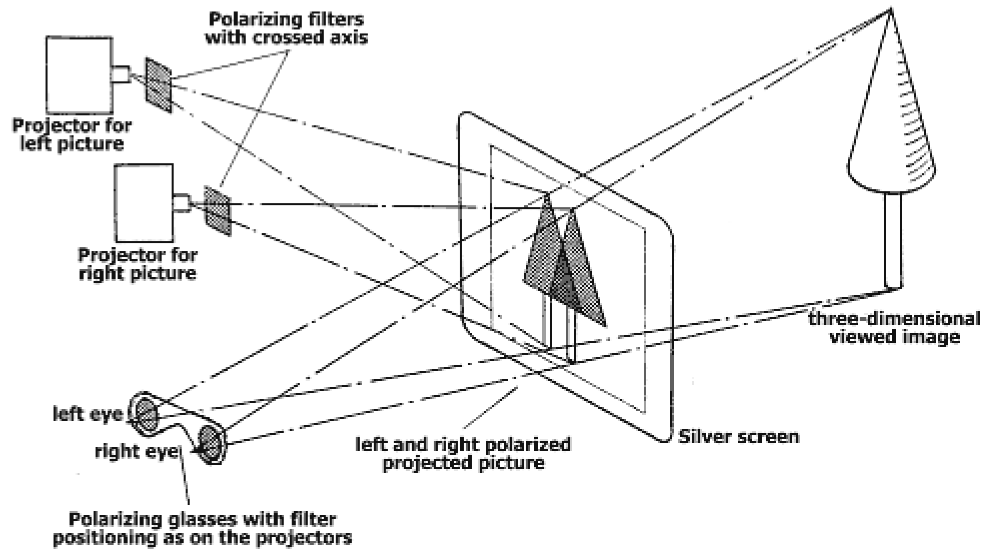
Source: http://www.studyphysics.ca

  - Most illumination from sources (sun, sky, lamps) is unpolarized.
  - Merely using a polarizer <u>will not remove</u> specular reflections <u>completely</u>

Applications of light polarization

- Active Illumination





Source: http://www.stereoscopy.com/faq/slideprojection.html

  – <u>Completely remove specular reflections</u> using polarized light when the <u>filters are 90 degrees apart</u>.
    - Commonly used in industrial settings
  – Also used in 3D cinema.

Mirrors

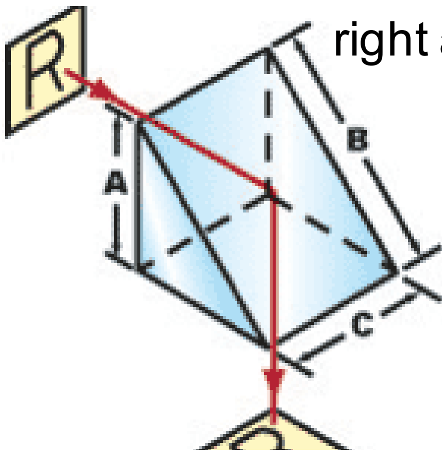
- Cold mirrors
  - Reflect visible light
  - Transmit infrared light

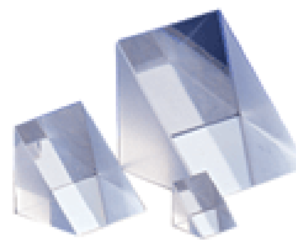
- Hot mirrors
  - Reflect infrared light
  - Transmit visible light

Prisms

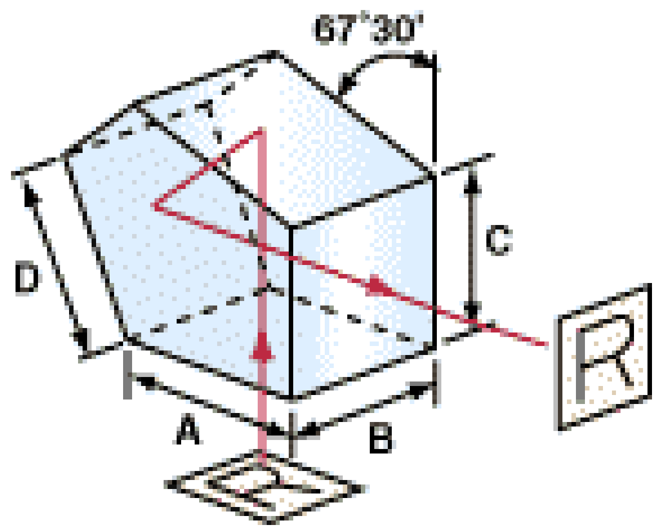
- Image reflection

right angle prism

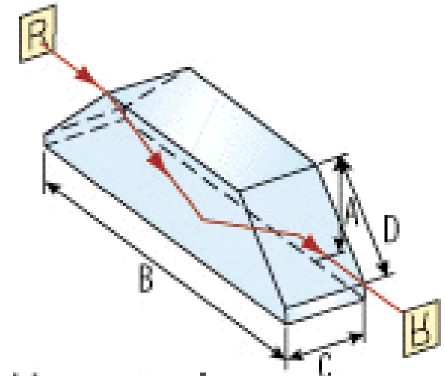




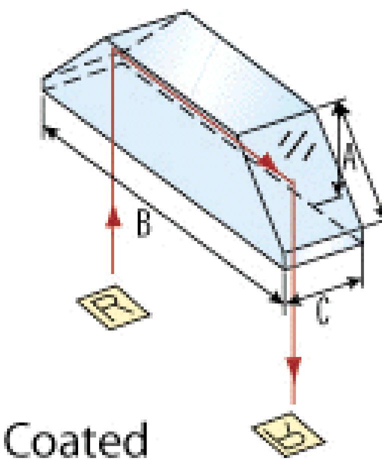
pent



- Image rotation



Uncoated



Coated

CAMERAS

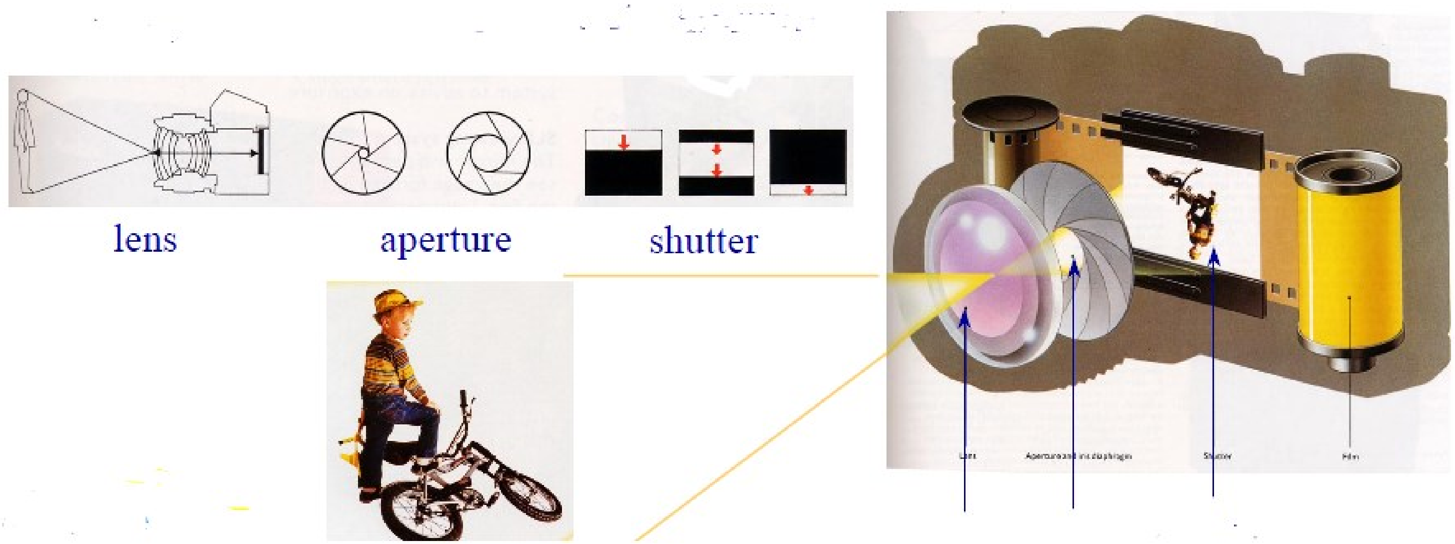
Photographic camera (film)

Main elements of a camera

- Lens– controlled by focusing ring and zoom
- Aperture – controlled by aperture ring
- Shutter – speed control
- Film

Goals

- Find the combination that achieves sharpest images for the largest range of scene with correct exposure



Digital camera

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
- Two common types
  - CCD - Charge Coupled Device
  - CMOS - Complementary Metal-Oxide Semiconductor

http://electronics.howstuffworks.com/digital-camera.htm

Shutter

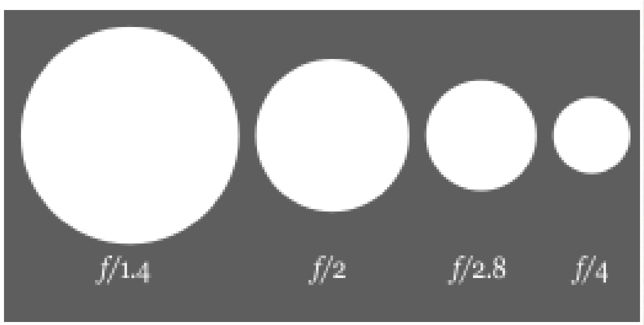
- The amount of time a film/sensor is exposed to the light
- A slow shutter speed causes motion blur
- 1/60 or 1/100 is good for common tasks

1/30 sec 1/125 1/500

(reprint from The Complete Kodak Book of Photography)

Aperture

- Usually expressed as <u>f-number</u>
  (focal ratio, f-ratio, f-stop, or relative aperture)
  - Is the <u>ratio of the lens's focal length to the diameter of the pupil</u>
  - f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22
- As the numbers get bigger, the aperture opening gets smaller
- Smaller aperture means sharper image (pinhole camera)

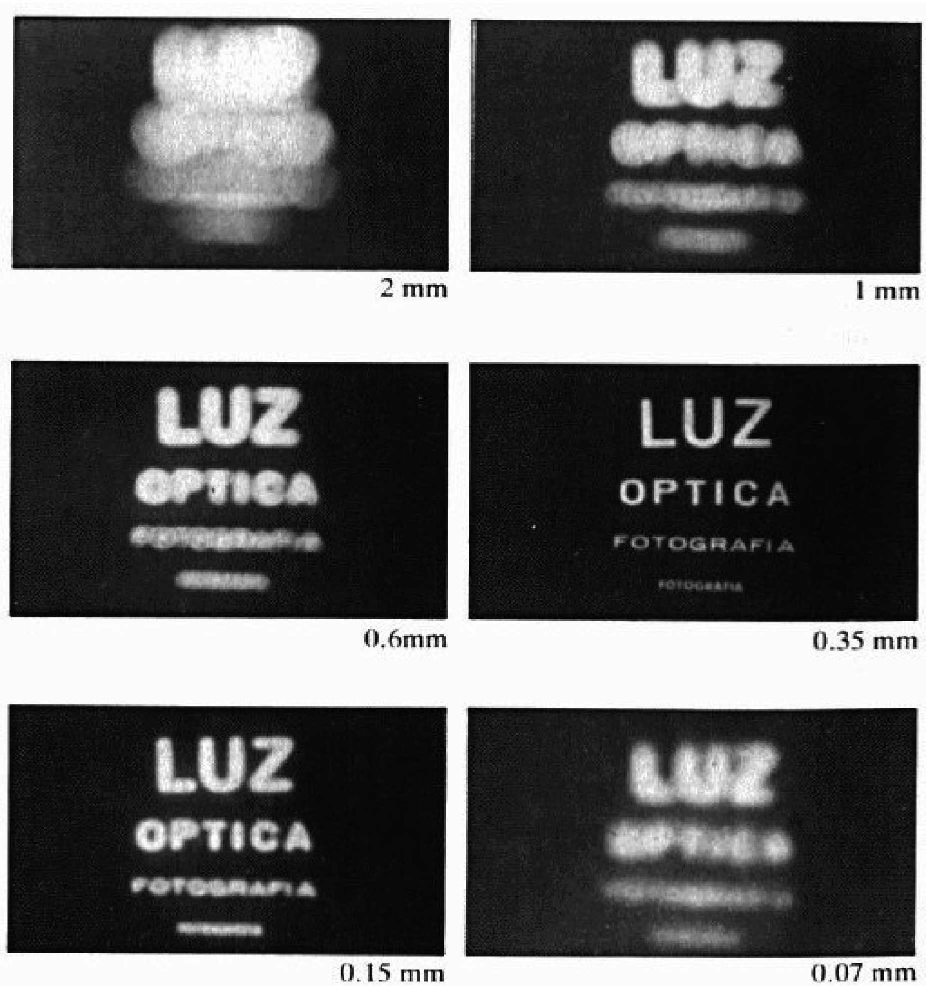


D = f / f-number

f/2 f/5.6 f/16

(reprint from The Complete Kodak Book of Photography)

Aperture

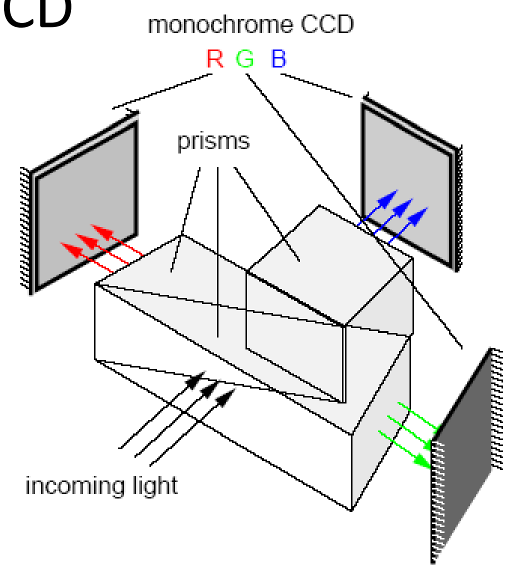


- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects

Sensors

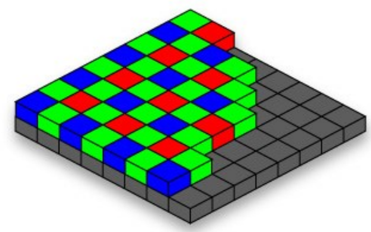
- Sensing color

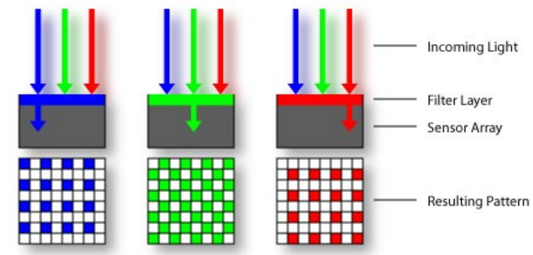
3 CCD



The incoming light is divided by prisms into its basic components: R,G, B

Bayer pattern





G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G

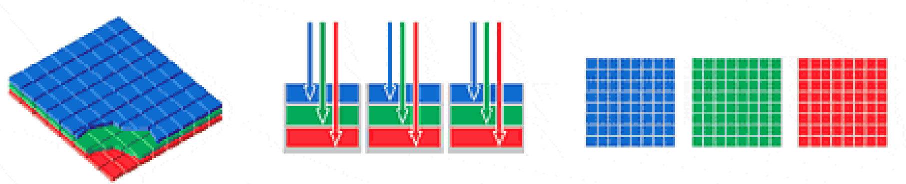
(a)

rGb	Rgb	rGb	Rgb
rgB	rGb	rgB	rGb
rGb	Rgb	rGb	Rgb
rgB	rGb	rgB	rGb

(b)

a) Filter array layout; b) interpolated pixel values, in lowercase

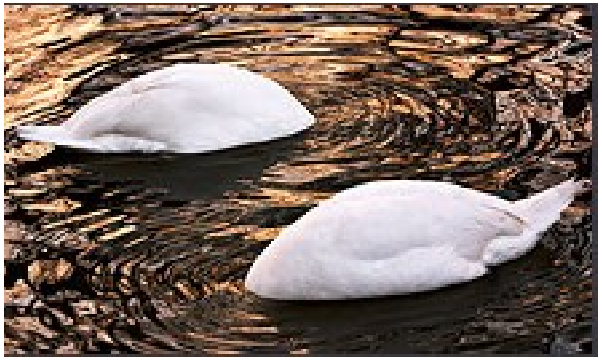
Foveon X3™



Dynamic range

- Dynamic range:
  - the range of **light** intensities from the darkest shadows to the brightest highlights;
  - for a real-world scene is simply the ratio between lightest and darkest regions (contrast ratio),
- A sunrise or sunset is what's known as a wide dynamic range scene, displaying a significant difference in exposure between the highlight and shadow areas in the frame. A scene with a narrow dynamic range has much more subtle differences between highlight and shadow areas, and as such, it's easier for a camera's sensor to record the full range of tones.

High dynamic range scenes

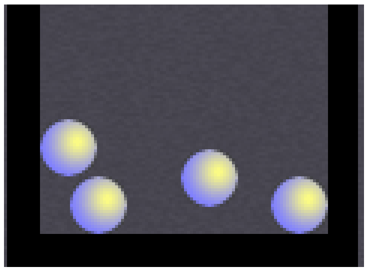


Strong reflections

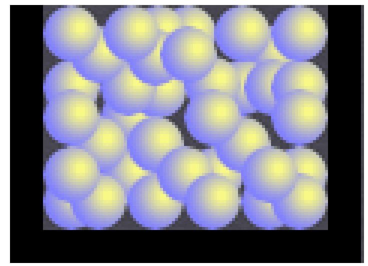
Uneven incident light

source: http://www.cambridgeincolour.com/tutorials/dynamic-range.htm

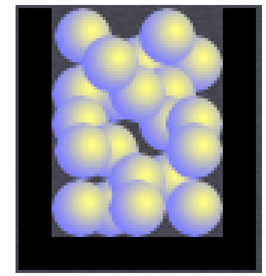
Dynamic range



Black Level
(Limited by Noise)



White Level
(Saturated Photosite)



Darker White Level
(Low Capacity Photosite)

- Photosites can be thought of as buckets which hold photons as if they were water. Therefore, if the bucket becomes too full, it will overflow.
- A photosite which overflows is said to have become saturated, and is therefore unable to discern between additional incoming photons — thereby defining the camera's white level.
- For an ideal camera, its contrast ratio would therefore be just the number of photons it could contain within each photosite, divided by the darkest measurable light intensity (one photon). If each held 1000 photons, then the contrast ratio would be 1000:1.
- Since larger photosites can contain a greater range of photons, **dynamic range is generally higher for digital SLR cameras compared to compact cameras** (due to larger pixel sizes).

source: http://www.cambridgeincolour.com/tutorials/dynamic-range.htm

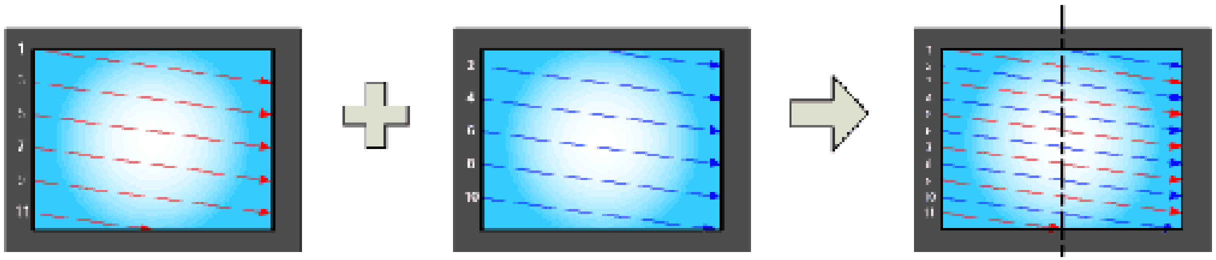
Exposure

- Ways to vary exposure
  - shutter speed
  - F/stop (aperture, iris)
  - neutral density filters
  - gain / ISO film speed

High Exposure Image

Low Exposure Image

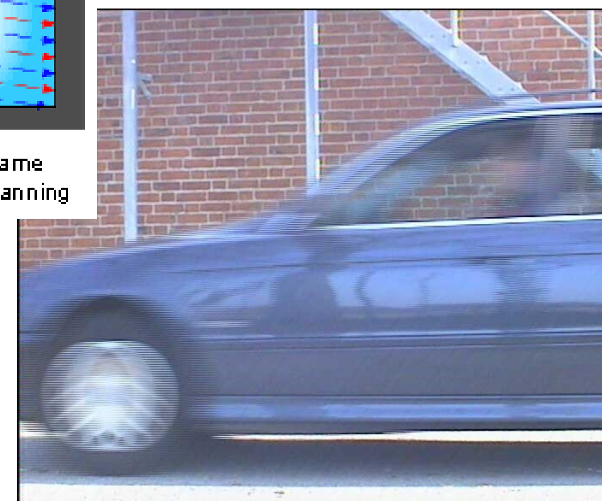
Video
Interlace vs Progressive scan

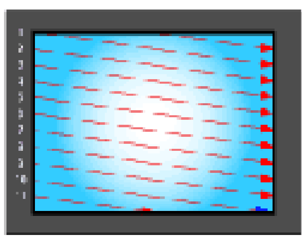


1st field: Odd field

2nd field: Even field

One complete frame using interlaced scanning





One complete frame using progressive scanning

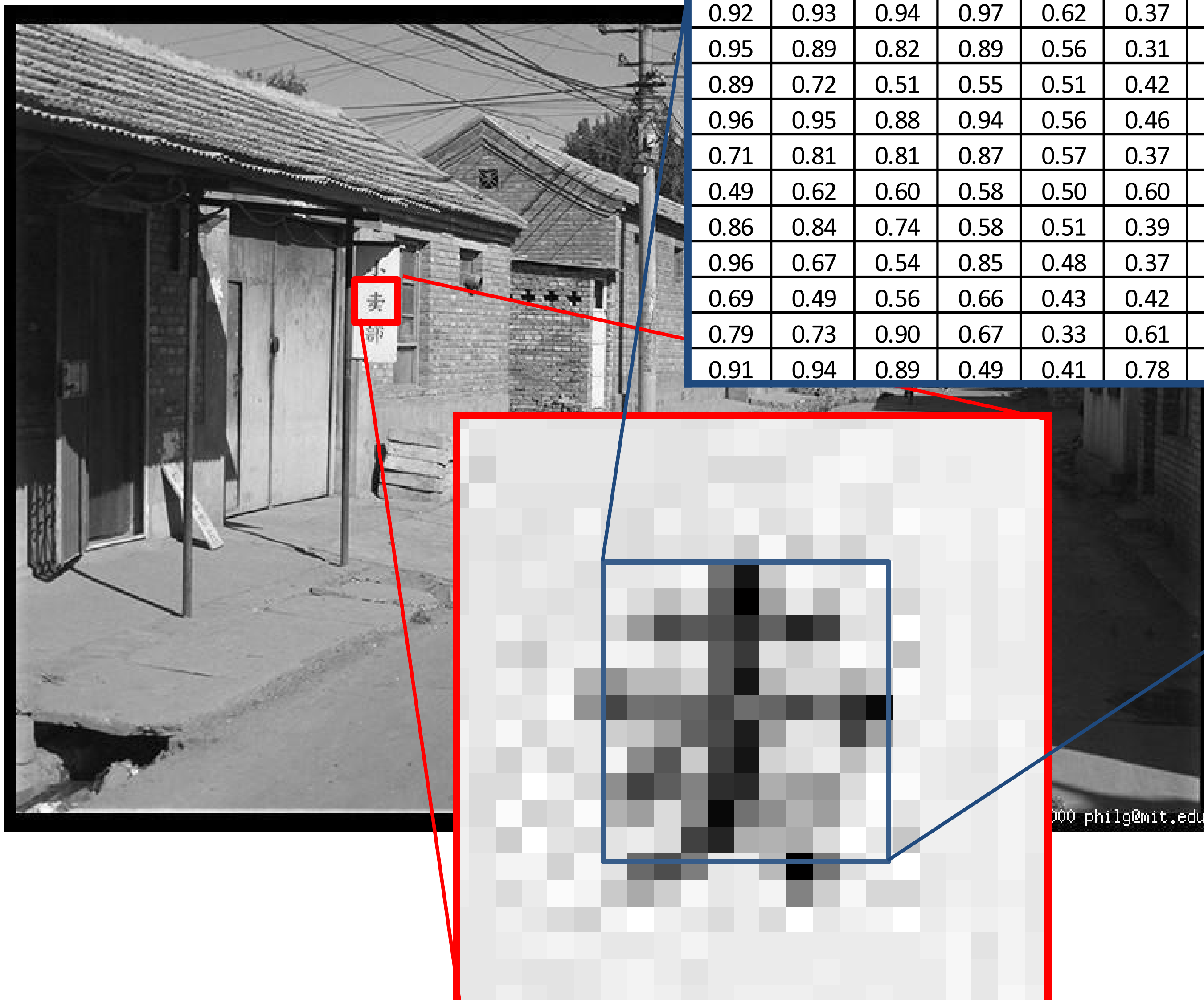
More information:
http://esupport.sony.com/perl/tutorial-display.pl?tut_id=411

Key factors for creating quality images

- Lighting
- Background
- Field of view
- Depth of field
- Exposure
- Color vs black and white

IMAGE REPRESENTATION

Grayscale images



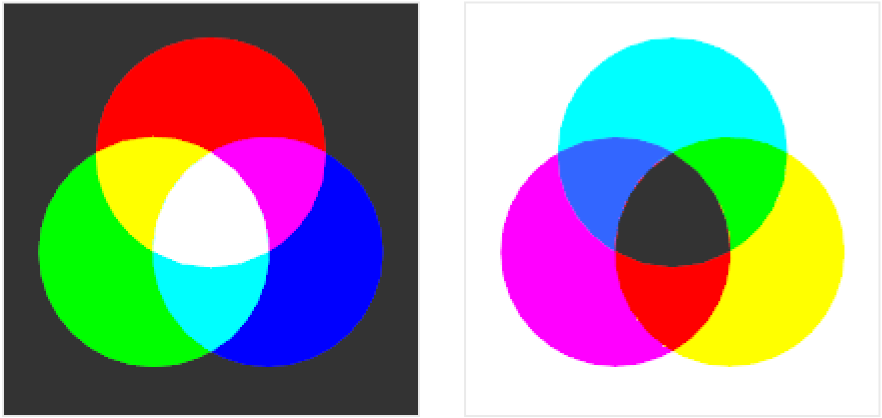
0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Note:
pixels values
may be integers

Color images

Color

- Primary and secondary colors
- Additive and subtractive colors



(a) (b)

Figure 2.27 Primary and secondary colors: (a) additive colors red, green, and blue can be mixed to produce cyan, magenta, yellow, and white; (b) subtractive colors cyan, magenta, and yellow can be mixed to produce red, green, blue, and black.

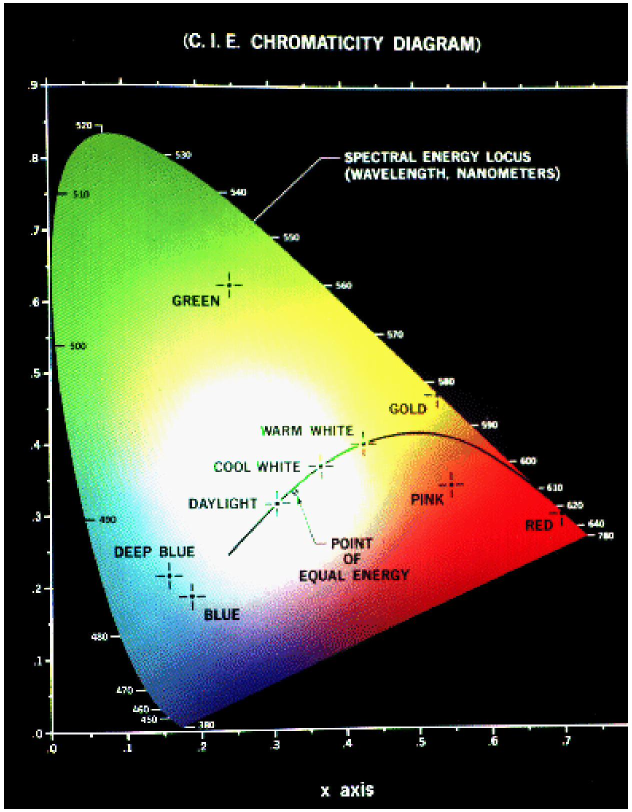
Source: Szeliski's book

Color spaces

- They provide a standard way of specifying a particular color using a 3D coordinate system.
- <u>Hardware oriented</u>:
  - RGB (monitors; additive)
  - CMY (printers; subtractive)
  - YIQ (NTSC video)
  - YUV (PAL video)
- <u>Image processing oriented</u>:
  - HSV / HIS / HSL / La*b* / Lu*v* / ...
    - The representations HSV, HSI and HSL are very similar, but not completely identical

Color spaces

- RGB
  - good for image capture
  - good for image display/projection (monitors)
  - good for storage
  - bad for user interfaces
    - how to modify the RGB components to obtain a specified color?
- HSV
  - good for user interfaces
  - H=hue (*matiz*)-- the "color wheel"
  - S=saturation (*saturação/pureza*) – how much gray ?
  - V=value – how much bright? ↔ brightness / luminance
  - non-linear transformation of RGB, given that H is cyclic
- YCrCb
  - good for compression
  - used by TV
- Other color spaces
  - La*b*
  - Lu*v*
  - YIQ (NTSC video)
  - YUV (PAL video)
  - CMY / CMYK - Cyan Magenta Yellow blacK (used in printers)
  - CIE XYZ
    - introduced by Commission Internationale de l'Éclairage
    - linear transformation of RGB



Color spaces

Fig. 13a. Color photograph.

Fig. 13b. CIELAB *L**.

Fig. 13c. Rec. 601 luma *Y′*.

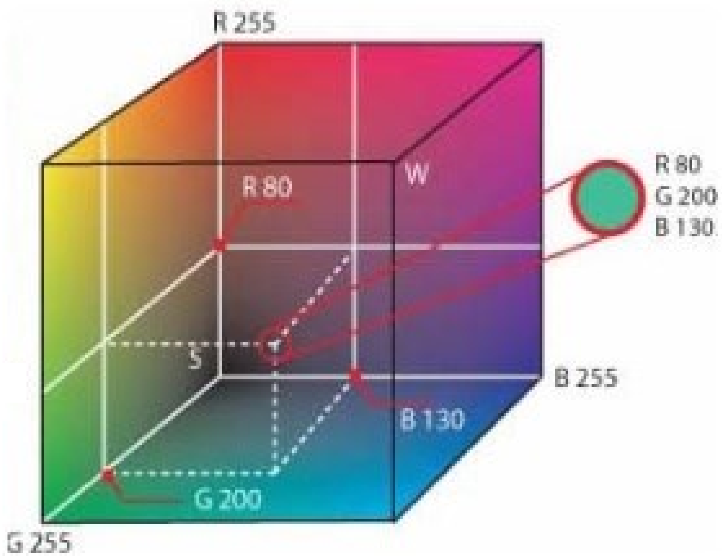
Fig. 13d. Component average: "intensity" *I*.

Fig. 13e. HSV value *V*.

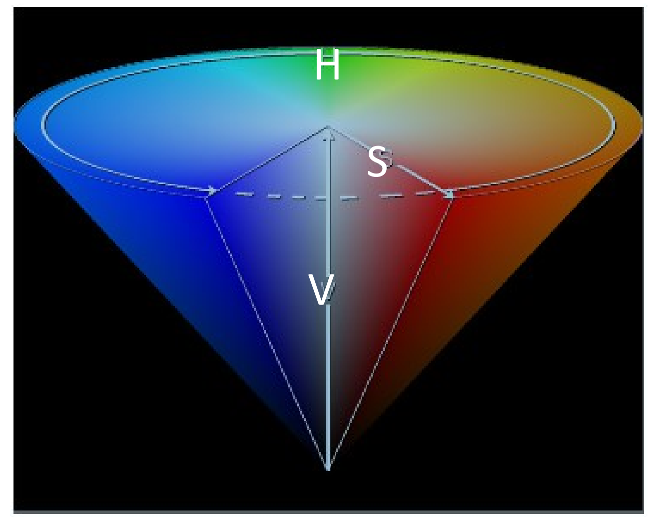
Fig. 13f. HSL lightness *L*.

https://en.wikipedia.org/wiki/HSL_and_HSV#Disadvantages

Color spaces

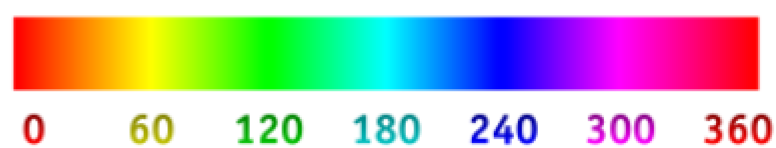


RGB



HSV

<u>Note</u>: the Hue of RED
ranges from ~330º - 30º (is not "continuous",
because of the transition 0º - 360º)

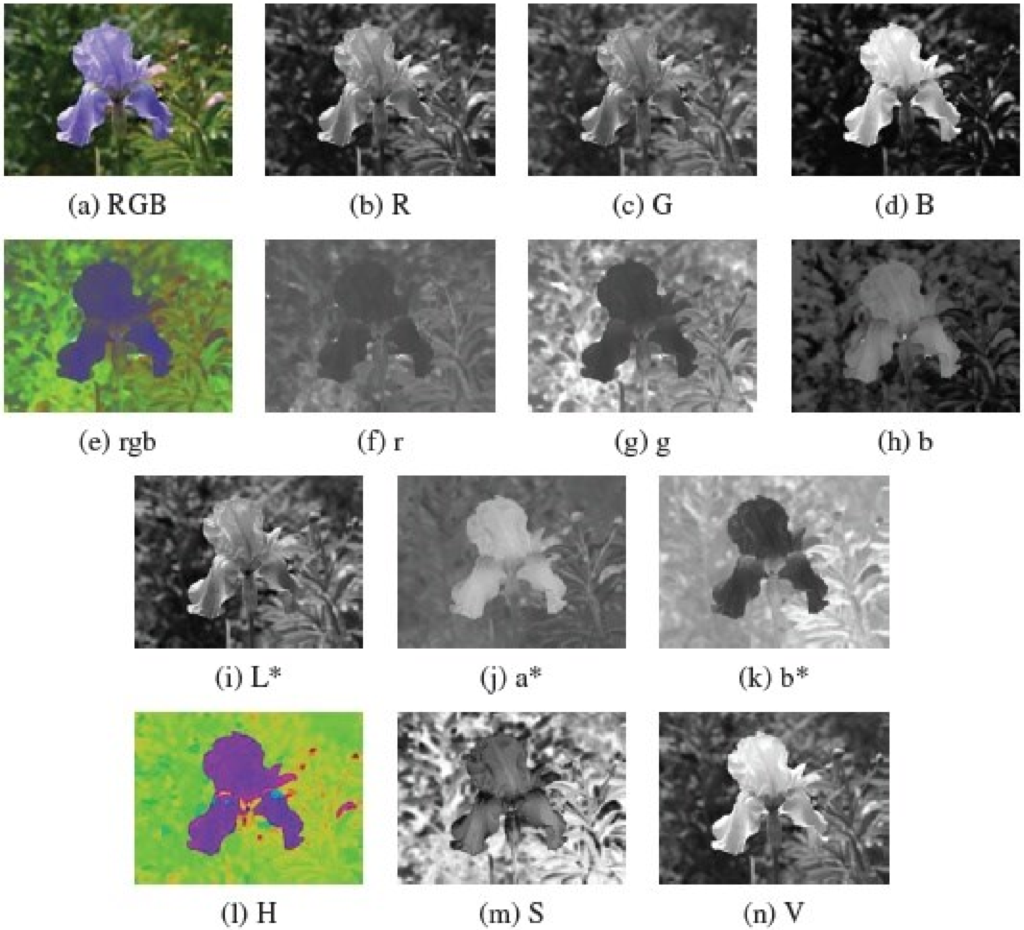


HSV

Figure 6.9: (Left) Input RGB image; (center) saturation S increased by 40%; (right) saturation S decreased by 20%. (Photo by Frank Biocca.)

source: Shapiro & Stockman

Color spaces



$$r = \frac{R}{R+G+B}, \quad g = \frac{G}{R+G+B}, \quad b = \frac{B}{R+G+B}$$

Figure 2.32 Color space transformations: (a–d) RGB; (e–h) rgb. (i–k) L*a*b*; (l–n) HSV. Note that the rgb, L*a*b*, and HSV values are all re-scaled to fit the dynamic range of the printed page.

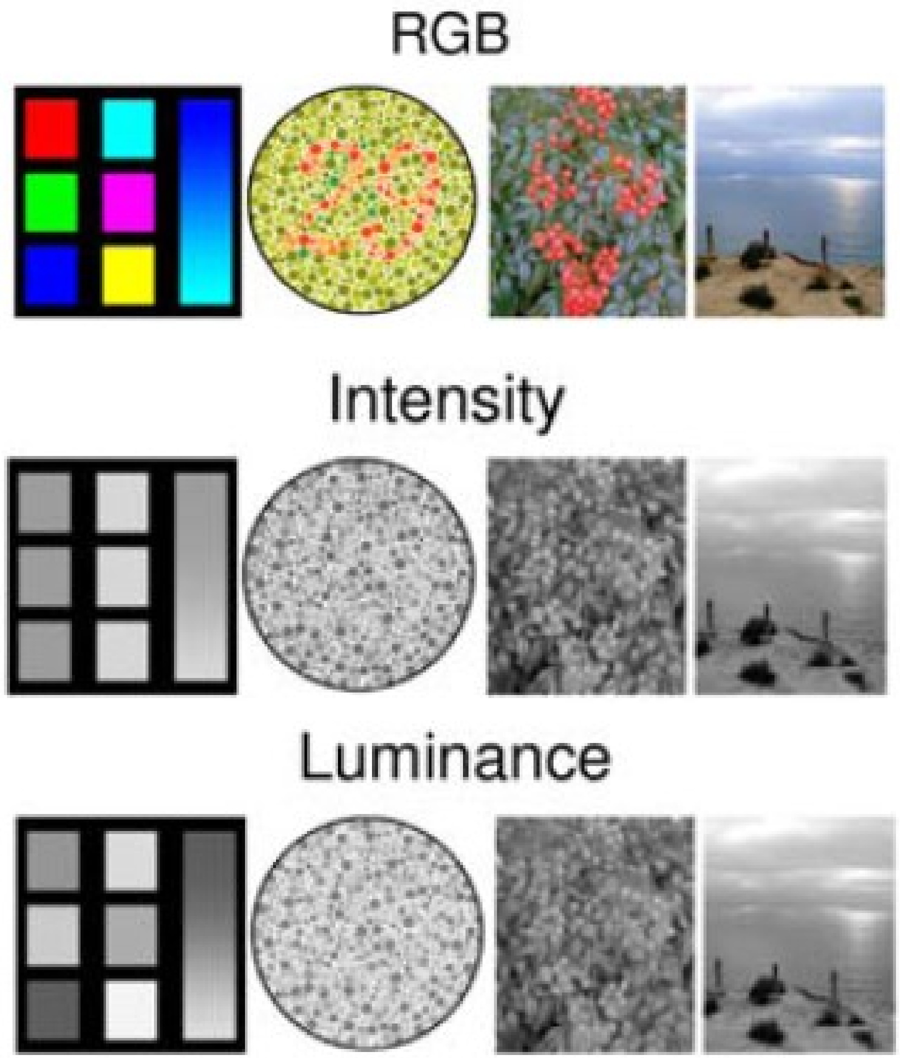
source: Szeliski's book

Converting color to grayscale

- How to convert a color image to grayscale?
  Many methods for converting to grayscale have been employed in computer vision.
- **Intensity**
  - averages the RGB values: (R + G + B) / 3.
- **Luminance**:
  - is designed to match human brightness perception
    by using a weighted combination of the RGB channels;
  - humans are more sensitive to green than other colors,
    so green is weighted most heavily: **Y= 0.299R + 0.587G + 0.114B**
  - is the standard algorithm used by GIMP and MATLAB's ''rgb2gray'' function.
- NOTE:
  - not all color-to-grayscale algorithms work equally well,
    even when using descriptors that are robust to changes in illumination

    http://tdlc.ucsd.edu/SV2013/Kanan_Cottrell_PLOS_Color_2012.pdf
    (compares 13 methods for converting color to grayscale)

Converting color to grayscale



3D PERCEPTION

How do humans see in 3D?

- Many distance / orientation cues ...
  - occlusion
  - texture gradient
  - perspective distortion
  - shading (illumination gradient)
  - shadows
  - …
  - stereoscopic disparity
- … but without being able to do obtain exact measures

Distance cues

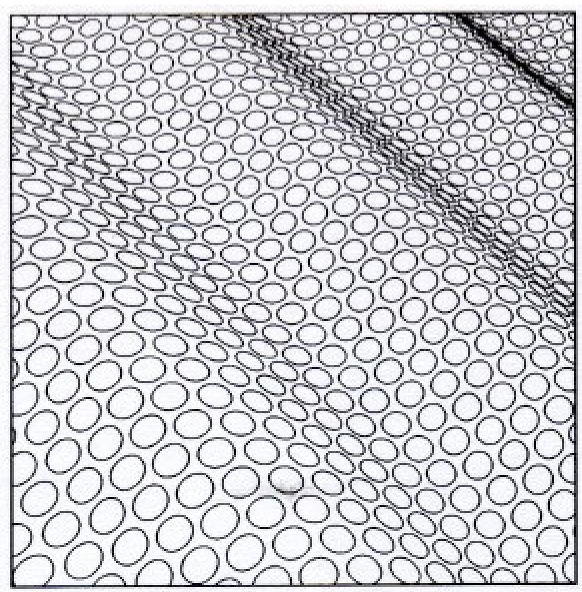
Occlusion & Perspective

Texture gradient

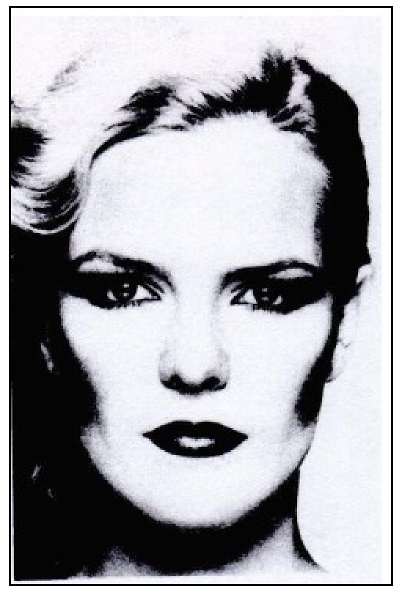
Distance cues

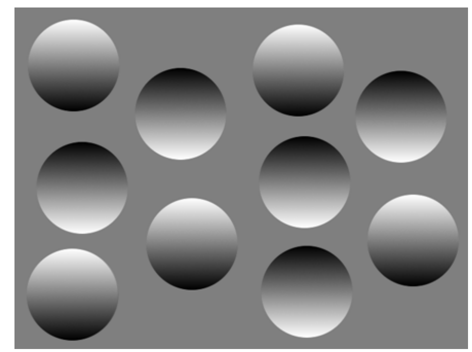
- Shape-from-X

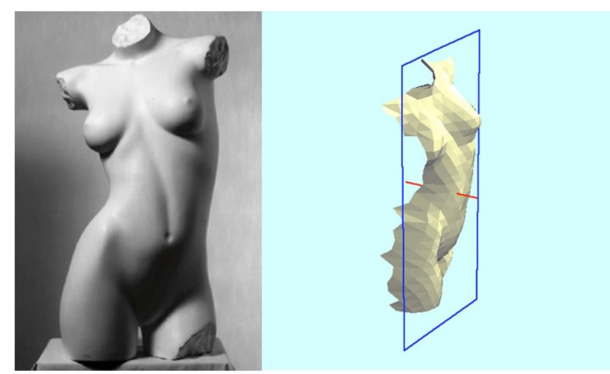
Texture



Shading







Distance cues

- Projected shadow(?!)
- Perspective distortion

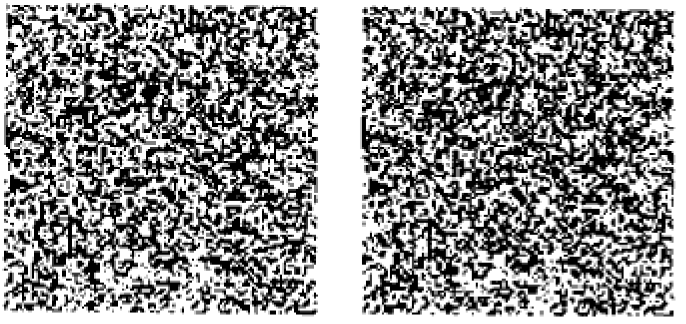
Source: J. Koenderink

slide credit: Svetlana Lazebnik

Binocular disparity

- *Random Dot Stereograms (RDS)*
  - pairs of images of random dots which when viewed with the aid of a stereoscope, or with the eyes focused on a point behind the images, produce a sensation of depth, with objects appearing to be in front of or behind the actual images
  - B. Julesz, 1971, theory on the basis of human stereo vision

- Process used to develop the first RDS
  - 1. Create an image of suitable size.
    Fill it with random dots.
    Duplicate the image.
  - 2. Select a region in one image.
  - 3. Shift this region horizontally
    by a small amount.
    The stereogram is complete.



Random dot stereogram from Julesz, 1971.

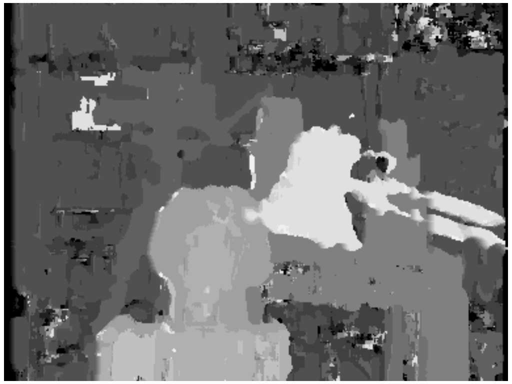
- The shifted region produces
  the binocular disparity
  necessary to give a sensation of depth.
  Different shifts correspond to different depths.
- Main conclusion:
  - depth can be perceived in the absence of any identifiable objects

Binocular disparity

- Stereoscopic pair disparity

Stereoscopic pair(Tsukuba)



Each point
represents the disparity
(difference in position in the images)
between corresponding points
in the 2 images of the stereoscopic pair

Disparity map

How do humans see in 3D ?

- … all the previous cues

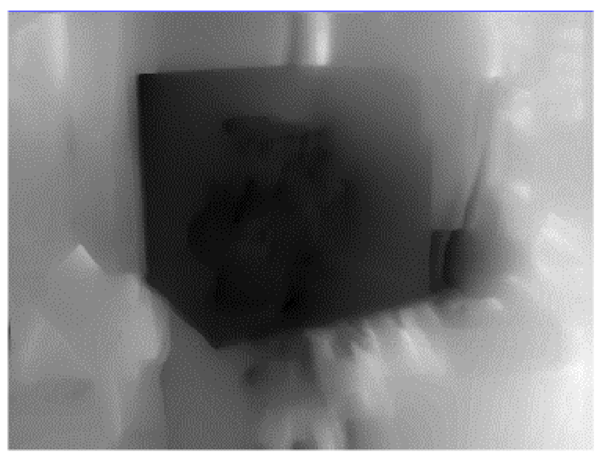
  +

- lots of acquired knowledge along one's life !!!

Relative size

Distance images

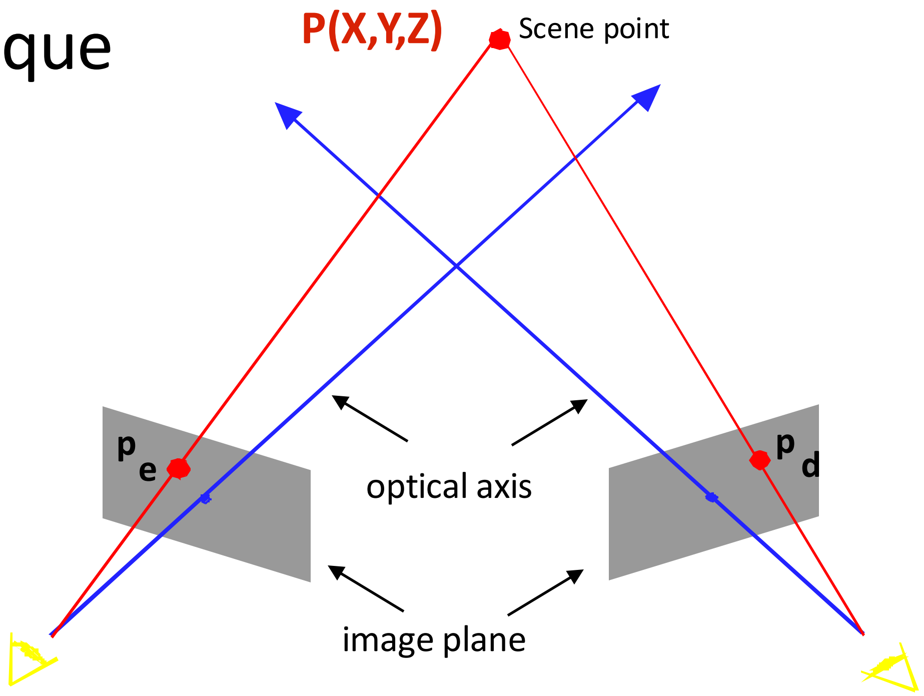
Stereoscopic pair of images



Distance image
(darker ⇒ closer)

3D image data acquisition

- Passive stereo technique



- The position (X,Y,Z) of P is obtained by triangulation.
- Corresponde problem:
  P_e and P_d must correspond to the same scne point P.

- Many other techniques can be used to acquire 3D data
  - ex: depth-from-focus (how ?), time-of-flight, optical flow …

Trucco & Verri

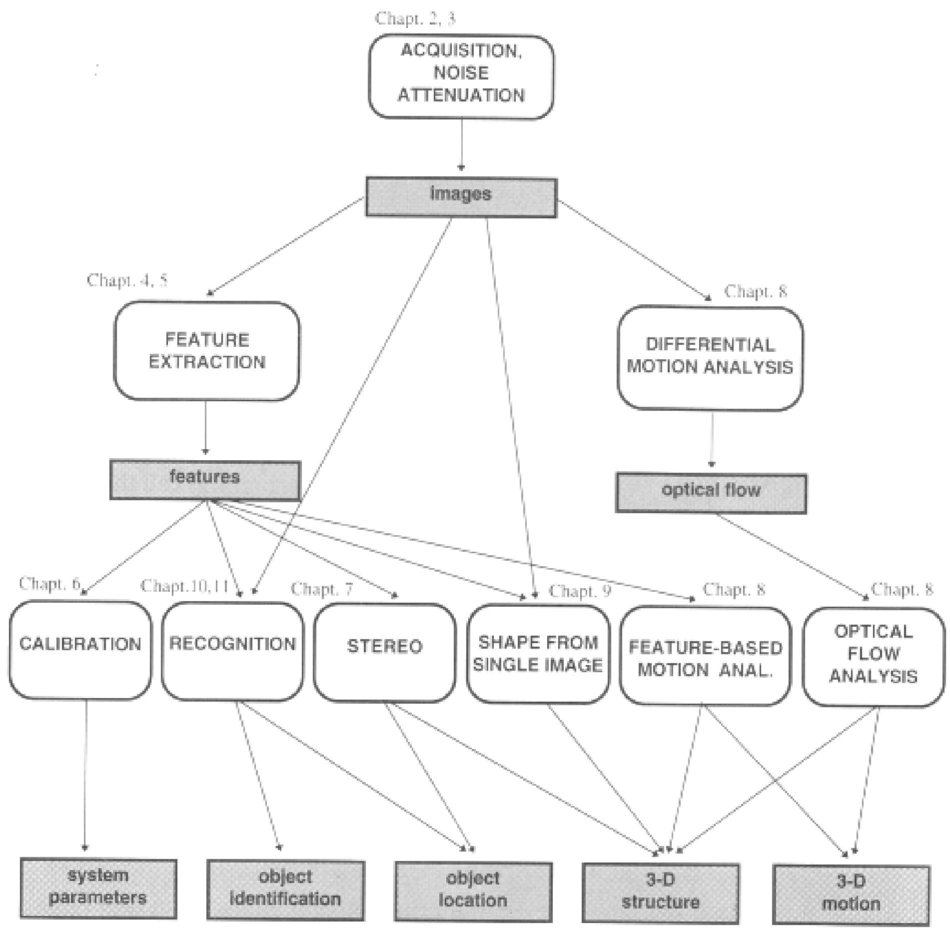


Figure 1.7 The book at a glance: method classes (white boxes), results (grey boxes), their interdependence, and where to find the various topics in this book.

How do humans see in 3D ?

- There have been many human biology/psychology experiments done in depth perception
  in which people are asked which object is front or back in scene.

- We are able to infer relative depth of some objects to others
  but our judgement about true depth is usually off.
  This means, we have poor abilities for stereo reconstruction.

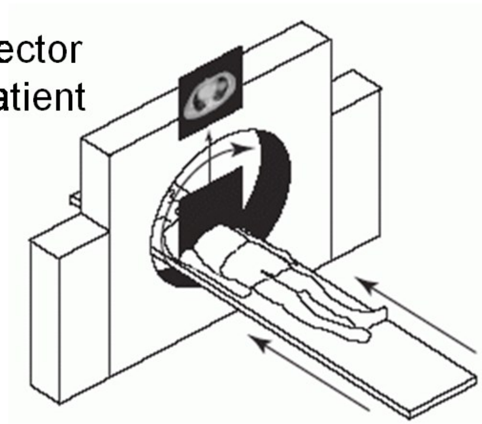
- <u>Human perception</u> is okay for relative depth
  but <u>is poor for real depth</u>.

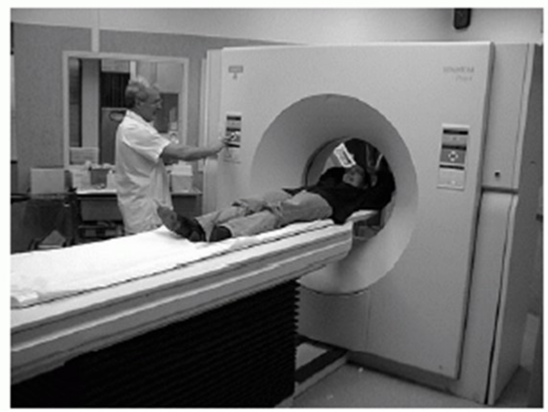
ACQUISITION OF
OTHER TYPES OF IMAGES

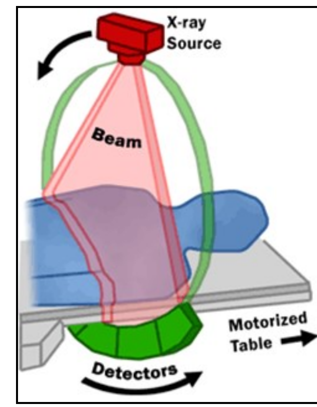
Tomographic images

- X-ray Computed Tomography (CT)

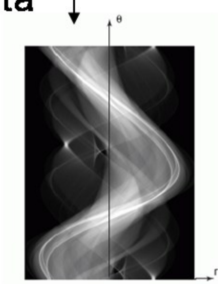
Scanning:
rotate source-detector pair around the patient



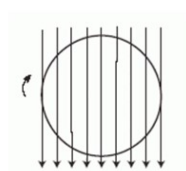




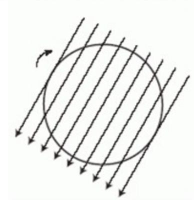
data

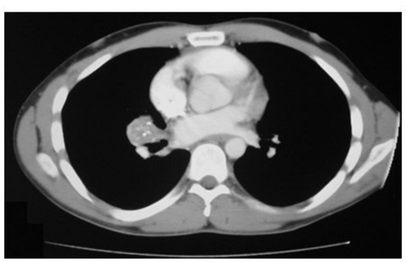


sinogram: a line for every angle



reconstruction routine





reconstructed cross-sectional slice